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Ice runways near the South Pole

Charles Swithinbank

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Following an examination of air photographs of the Transantarctic Mountains, 37 blue-ice areas were reconnoitered from the air, using a ski-wheel Twin Otter operating from the South Pole. Two sites were selected as potential airfields for conventional transport aircraft, and ground surveys were made. On the Mill Glacier at 85°06'S, 167°15'E there is an area of smooth and level ice which gives a 7-km run directly into the prevailing wind. Five wheel landings were made there. Alongside Mount Howe there is a large area of level ice at 87°20'S, 149°50'W. It offers a 7-km runway, but there is a strong crosswind component from the prevailing wind and some bumps on the ice surface need to be planed off. Eight wheel landings were made at Mount Howe.

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PREFACE

This project was carried out on behalf of the Division of Polar Programs, National Science Foundation (DPP/NSF). The work was part of the 1988–89 program of Antarctic Engineering Services provided to DPP/NSF by U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) (CC: 9 6000 70 701). Dr. Charles Swithinbank carried out the field work and prepared the report under a contract arranged by the European Research Office of the U. S. Army. The project was directed by Dr. Malcolm Mellor, Experimental Engineering Division, CRREL.

The author is grateful to the many people who contributed to the field work, and to the supporting organizations (NSF, NSFA, VXE-6, ITT/ANS, CRREL). He is particularly grateful to: the pilots and engineers of the Kenn Borek Twin Otters (Brydon Knibbs, Brian McKinley, Bob Allen, George Cox, Tony Frigon, Clark Boutin); the South Pole personnel who assisted at the station and in the field (Bill Coughran, Bob Hurtig, Ray Brudie, Doug Chichester, Kay Tate, John Gushwa, Valerie Sloan, Mark Parent, Bill Spindler); the air photography specialists (Gerry Mullins, Pat Gropp); and the CRREL personnel (Steve Den-Hartog, Malcolm Mellor and Wayne Tobiasson).

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INTRODUCTION

The surface of most of the Antarctic ice sheet consists of snow. In places the snow is hard, in places soft. At any given point, the hardness increases with the age of the snow. The principal parameters affecting it are wind, precipitation, deflation, and sublimation (evaporation). However, there are also thousands of square kilometers of snow-free bare ice. The bare ice areas have become known in scientific literature as blue icefields. Their principal characteristic is that they occupy a surface equilibrium zone in which there is very little surface net accumulation or net ablation. Some aluminum survey markers that I myself drilled into the surface of a blue icefield in 1951 were found still standing 34 years later. Changes in the exposed length averaged less than 3 cm/yr (Brunk and Staiger, 1986).

Schytt (1960) has discussed the origin of blue icefields. I became aware of the existence of extensive icefields in the Transantarctic Mountains while working and traveling in the area 1960-1962 (Swithinbank, 1964). My interest in their potential as landing areas for transport aircraft dates from 1967, when I flew 94 hours in VX-6's C-121J (Super Constellation) Phoenix 6. With wheeled landing gear, this aircraft could operate only from the sea ice runway at McMurdo. Some of our flights were of 12 hours duration, and it occurred to us that McMurdo might be weathered-in by the time we got back. The pilot, LCDR J K Morrison, said that in that case his orders were to 'ditch' (if that is the word) wheels-up somewhere on the Ross Ice Shelf. The machine would be a write-off, and in theory at least, we would simply walk off. This policy struck me as an incitement to waste taxpayer's money.

Although LC-130 and C-141 aircraft frequently make wheel landings on sea ice at McMurdo, and Soviet transport aircraft have landed on lake ice at Bunger Hills, there has been only limited interest in the potential of inland icefield runways. The attraction of a well-chosen blue-ice runway is that construction and maintenance costs are almost nil (Mellor, 1988). Kovacs and Abele (1977) investigated two inland ice runways in the Pensacola Mountains, finding a 2500 m (8200 ft) site at an elevation of 800 m (2600 ft) above sea level and a 3000 m (9800 ft) site at 1400 m (4600 ft) above sea level. They concluded that both of these were suitable for C-130 and C-141 operations, even allowing for the extra length dictated by their elevation. The natural ice surfaces were "not unlike those of field runways". The amplitude of surface relief was 1-2 cm (1 inch). Other sites were reconnoitered from the air and the authors concluded that sites suitable for C-5 aircraft could probably be found. Owing to lack of interest, however, no further studies were made.

A DC-4 belonging to Kenn Borek Air Ltd of Calgary made 12 flights between Punta Arenas (Chile) and an icefield at Patriot Hills (Heritage Range) during the 1987/88 Antarctic season (Swithinbank, 1988a). Fifteen flights were made during the 1988/89 season. Each flight involved an unrefuelled round-trip distance of 6150 km (3320 nm).

NARRATIVE

In August 1988 I examined some 7000 aerial photographs obtained for mapping purposes by the US Navy for the US Geological Survey between latitudes 84°S and 88°S, longitudes 160°E and 120°W (Swithinbank, 1988b). The majority of useful photographs were high obliques. However, a typical viewing distance for features on the ground was 15 km, of which 6 km was represented by the height of the aircraft. From this distance it was impossible to estimate, and sometimes even to perceive, slopes in the range 1-10% Thirty seven sites appeared to have smooth ice surfaces with minimal snow cover, but it was predicted that most of them would prove unsuitable for transport aircraft on grounds of slope, grade change, length, crevasses, or obstructed approaches. There being no easier way, a reconnaissance of all of them from a low-flying Twin Otter aircraft was recommended.

I arrived at McMurdo station on 2 December 1988, and after assembling camping gear and survey instruments, flew to South Pole on 8 December. Twin Otter C-GKBG arrived at South Pole the following day and reconnaissance flights were made on 10 and 11 December, after which the aircraft was required at McMurdo for duties unconnected with the project. The aircraft returned to South Pole on 19 December and reconnaissance flights were resumed on 20th.

It rapidly became clear that the icefield at Mount Howe, considered the prime site in view of its proximity to South Pole (300 km or 160 nm), might well meet the principal criteria for operating large aircraft. Accordingly, it was decided to set up camp there in order to undertake optical leveling. As a need for camping before early January had not been anticipated, there were no field assistants on hand. However, the aircrew of C-GKBG kindly volunteered to serve in this capacity and a camp was established on the icefield on 21 December. The camp was secured late on 24 December but left intact, and we returned to South Pole for Christmas.

There were numerous volunteers for subsequent camps, so it was agreed that while the icefield party was in camp, the aircraft could be made available for other duties. A 4-person party was landed at Mount Howe on 27 December to resume survey work. In the course of many miles of walking over the ice, a 2.5 kg (5.5 lb) iron meteorite was recovered. On completion of the survey on 29 December the party was returned to South Pole.

Reconnaissance flights resumed on 2 January 1989 and in the course of them, our meteorite was handed to Professor W A Cassidy at his Lewis Cliff camp and two of his party were taken to Mount Howe to search for more. At this time it became clear that an icefield on Mill Glacier adjacent to Plunket Point also met essential criteria for use as an ice runway, so a 4-person survey party was landed there on 4 January. After returning to South Pole, C-GKBG flew to Siple Coast to assist the work there until called to recover the Mill icefield party.

By happy coincidence a US Geological Survey party was using a Zeiss LMK-15 survey camera in one of the Twin Otters working on the Siple Coast project. We asked that when their work was finished, they should return to McMurdo via South Pole and photograph our two sites with a view to preparing a photo-mosaic at a scale of 1:10,000. Although the ground surveys had been planned for optical leveling and not for mapping control, it was agreed that the opportunity should not be missed. Accordingly, C-GKBG flew from Siple Coast to South Pole on 9 January with the camera and its operator.

The Mill icefield survey was now finished, so C-GKBG was asked to return the Mount Howe meteorite party to their main camp at Lewis Cliff, and en route back to South Pole, to recover the Mill icefield party. This was accomplished on 10 January (the meteorite party meanwhile having added three meteorite fragments to their collection). On arrival at South Pole, the survey camera was refitted in the aircraft and the Howe icefield photography was successfully completed early on 11 January. The Mill icefield photography was accomplished the following day while C-GKBG was en route to McMurdo.

It had become evident that ice runways at Mount Howe could be improved by planing, so Dr Malcolm Mellor was requested to come to South Pole to advise on suitable planing machinery. He arrived from 'Upstream C' with Twin Otter C-FSJB on 21 January. Both the Mill and the Howe icefields were visited on 22 January and the Howe icefield again on 23 January. Engineers Wayne Tobiasson, Stuart Osgood, and William Spindler were taken to one or other of the icefields to render a second opinion. All essential work being completed, C-FSJB left the following day for Calgary.

By combining missions whenever possible and making use of positioning flights for reconnaissance, Twin Otter flying directly attributable to the project totalled 72 hours. Nineteen out of twenty operations were undertaken on the day required. One flight was aborted by low cloud and another was unproductive through failure of a ground refuelling pump. No flights were lost through technical problems with either aircraft.

All landings on the icefields were made on wheels and at no time were there any difficulties. Eight landings were made on Howe icefield and five on Mill icefield. Since the fuel caches requested in advance of the season were not in place when needed, C-GKBG flew heavy with fuselage tanks for some reconnaissance flights. This tended to inhibit further trial landings. A 1000-gallon fuel cache was, however, placed by LC-130 beside Lhasa Nunatak and this proved a great help for flights in connection with the Mill icefield survey. Both sealdrums used for the cache were recovered by C-GKBG and returned to McMurdo.

SITE RECONNAISSANCE

Of the 37 sites identified from aerial photographs as possible runway sites, 30 were inspected from the air. The remaining sites were rejected without on-site inspection when it became clear that none of them could match up to sites closer to South Pole. In discussing them in ascending order of distance from South Pole, we will use the same site numbering convention used in the earlier report (Swithinbank, 1988b). The TMA numbers refer to aerial mapping photographs available from the US Geological Survey, National Center, Reston, VA 22092.

Dimensions of possible runway sites were estimated in the course of overflights. No dimensions are reported for icefields considered unusable. Where lengths are rounded to the nearest kilometer, they are based on overflights at heights of around 300 m (1000 ft), generally scaled with the help of maps and air photographs. Dimensions rounded to 100 m (300 ft) result from a low pass at a height of about 10 m (30 ft) scaled by means of INS ground-speed and stopwatch.

It is not possible to judge the degree of slope of an almost-level icefield from the air. However, areas obviously having a slope of 2% or more were rejected.

Site 1: Mount Howe (d'Angelo Bluff map sheet)
87°20'S, 149°50'W, elevation 2400 m (7900 ft), TMA 1203 F31 045.
This has the best potential for ice runways accessible overland from South Pole. It was the subject of close examination from the ground (see HOWE ICEFIELD on page 9).

Site 2: Mount Prestrud (Mount Wisting map sheet)
86°33'S, 165°20'W, elevation 2350 m (7700 ft), TMA 1135 F31 137.
This is a 2400 x 1000 m (7900 x 3300 ft) icefield off a lateral moraine on the west side of Mount Prestrud (Norway Glacier). The ice surface appears smooth and usable as an ice runway.

Site 3: Amundsen Glacier (Nilsen Plateau map sheet)
86°29'S, 159°35'W, elevation 2050 m (6700 ft), TMA 1135 F33 117.
This icefield is along the right bank of Amundsen Glacier below Nilsen Plateau. The surface appears smooth but unacceptable owing to waves in the long profile.

Site 4: Mount Hassel (Nilsen Plateau map sheet)
86°27'S, 164°10'W, elevation 1900 m (6200 ft), TMA 1135 F33 135.
This is off a lateral moraine on the right bank of Devil's Glacier below Mount Hassel. It is short, steep, and crevassed.

Site 5: Mount Ruth (Nilsen Plateau map sheet)
86°18'S, 151°50'W, elevation 1400 m (4600 ft), TMA 1209 F31 027.
This icefield is on the right bank of Bartlett Glacier below Mount Ruth. We were unable to approach it owing to turbulence. It looks too steep and undulating to be of interest.

Site 6: Ackerman Ridge (Mount Blackburn map sheet)
86°35'S, 148°25'W, elevation 1700 m (5600 ft), TMA 1462 F33 114.
This is a 4000 x 3000 m (13,000 x 10,000 ft) icefield off a lateral moraine on the right bank of Scott Glacier below Ackerman Ridge. The ice surface appears smooth but the area is surrounded on 3 sides by mountains.

Site 7: Robison Glacier (Mount Blackburn map sheet)
86°30'S, 148°00'W, elevation 1650 m (5400 ft), TMA 1135 F33 076.
There are large areas of ice downstream from Mount Mooney but they are crevassed and thus not of interest.

Site 8: Mount Roland (Mount Blackburn map sheet)
86°28'S, 145°20'W, elevation 1950 m (6400 ft), TMA 789 F31 243.
This is a small intermontane plateau between Mount Suarez, Mount Roland, and Szabo Bluff but it appears to have obstructed approaches on three sides. We did not approach it.

Site 9: Mount Pool (Caloplaca Hills map sheet)
86°13'S, 127°40'W, elevation 1750 m (5700 ft), TMA 1135 F33 001.
This icefield was found to be crevassed.

Site 10: Mount Emily (Plunket Point map sheet)
85°50'S, 173°50'E, elevation 2550 m (8400 ft), TMA 1156 F31 132.
This icefield appeared to consist of less dense ice, and smooth sections between moraine or snow obstructions were too short.

Site 11: Davis Nunataks (Plunket Point map sheet)
85°37'S, 167°00'E, elevation 2400 m (7900 ft), TMA 775 F33 122.
The main area of this icefield south of an east-west trending moraine loop is unusable because of its slope and bumpy surface. However, a 4300 x 100 m (14,000 x 300 ft) strip parallel with the moraine loop and close to it on the north side would be usable. It was 10% snow covered at the time of our visit but this would not prevent safe operation of C-130 or C-141 aircraft on wheels.

Site 12: Mount Bumstead (Plunket Point map sheet)
85°39'S, 173°55'E, elevation 2450 m (8000 ft), TMA 784 F31 192.
This is a 5000 x 2000 m (16,000 x 6600 ft) icefield that could yield a very smooth east-west runway. However, on our visit it appeared to consist of less dense ice than the other icefields. It would be worth another visit to see if it looks the same every year.

Site 13: Supporters Range (Plunket Point map sheet)
85°10'S, 169°45'E, elevation 1850 m (6100 ft), TMA 774 F31 092.
This icefield is against the right bank of Mill Glacier beneath Supporters Range. The slope was found to be too great.

Site 14: Mill Glacier (Plunket Point map sheet)
85°05'S, 166°12'E, elevation 1800 m (5900 ft).
This has the best potential for ice runways on the direct route between McMurdo and South Pole and is accessible for surface vehicles. It was the subject of close examination from the ground (see MILL ICEFIELD on p.24).

Site 15: Ellis Bluff (Liv Glacier map sheet)
$85^{\circ}22'S$, $175^{\circ}50'W$, elevation 2000 m (6600 ft), TMA 1432 F31 143.
This is a 6900 x 900 m (22,000 x 3000 ft) icefield on a distributary tongue from Zanefeld Glacier. The up-glacier approach would be through a pass (at runway level) at the foot of the ice tongue. The surface appears smooth with almost no snow cover. However, it would not be easy to find an overland route to South Pole.

Site 16: Baldwin Glacier (Liv Glacier map sheet)
$85^{\circ}06'S$, $177^{\circ}00'W$, elevation 1400 m (4600 ft), TMA 781 F33 058.
This is a gently sloping (probably less than 1%) tributary of Shackleton Glacier. A timed run up the middle of Baldwin Glacier indicated a usable length of 6800 m (22,000 ft), though a landing aircraft would face into a 500 m (1600 ft) high rock wall. The surface was smooth and snow-free but there was a small melt-stream flowing across the southern half of the glacier. The adjacent Gallup Glacier has too many cracks to be of interest.

Site 17: Mount Zanuck (Mount Goodale map sheet)
$85^{\circ}55'S$, $151^{\circ}00'W$, elevation 900 m (3000 ft), TMA 1209 F31 013.
We were unable to approach this area owing to turbulence. The evidence of undulations and its limited dimensions make it unattractive.

Site 18: Mount Hamilton (Mount Goodale map sheet)
$85^{\circ}44'S$, $152^{\circ}05'W$, elevation 650 m (2100 ft), TMA 780 F33 144.
We were unable to approach this area owing to turbulence. Its limited dimensions make it unattractive.

Site 19: Koerwitz Glacier (Mount Goodale map sheet)
$85^{\circ}40'S$, $154^{\circ}05'W$, elevation 500 m (1600 ft), TMA 780 F33 138.
This icefield was found to have too much slope and too much moraine scattered over the surface.

Site 20: Mount Salisbury (Mount Goodale map sheet)
$85^{\circ}35'S$, $153^{\circ}50'W$, elevation 400 m (1300 ft), TMA 780 F32 138.
This also proved to have too much slope and too much moraine scattered over the surface.

Site 21: Scott Glacier (Mount Goodale map sheet)
$85^{\circ}27'S$, $154^{\circ}00'W$, elevation 150 m (500 ft), TMA 780 F31 138.
This icefield is undulating and in places pock-marked by melting.

Site 22: Mount Nichols (Leverett Glacier map sheet)
$85^{\circ}26'S$, $147^{\circ}00'W$, elevation 200 m (600 ft), TMA 823 F31 007.
The icefield between Supporting Party Mountain and Mount Graham has crevasses and melt holes. However, between Mount Nichols and Mount Manke there is a beautiful smooth icefield without cracks and with dimensions of at least 5000 x 1000 m (16,000 x 3000 ft). It is seen from a distance in TMA 780 F31 161.

Site 23: Berry Peaks (Leverett Glacier map sheet)
$85^{\circ}25'S$, $139^{\circ}30'W$, elevation 500 m (1600 ft), TMA 856 F31 149.
This icefield is for the most part too undulating to be of interest, though parts might be usable between areas with small cracks.

Site 24: Harold Byrd Mountains (Leverett Glacier map sheet)
85°24'S, 147°30'W, elevation 200 m (600 ft), TMA 823 F31 010.
This is an ice-covered lake which proved to be pock-marked by ablation, probably soft, and cracked.

Site 25: Colorado Glacier (Wisconsin Range map sheet)
85°54'S, 133°20'W, elevation 1350 m (4400 ft), TMA 598 F33 074.
This icefield proved on inspection to be sloping and bumpy.

Site 26: Reedy Glacier (Wisconsin Range map sheet)
85°45'S, 133°00'W, elevation 1200 m (4000 ft), TMA 780 F33 199.
There are vast areas of smooth ice along some flow bands of Reedy Glacier between the 1000 m and 1400 m contours, perhaps best developed around the 1200 m contour. The average longitudinal gradient is less than 1%. Some of the flow bands look as if they could accommodate a landing space shuttle. There is a 5% snow cover in some areas but this is generally in the form of sastrugi less than 10 cm high and thus not significant for wheeled aircraft. The advantage of the area is that prevailing winds, particularly between the 1200 m and 1400 m contours, are down-glacier. The approach and climb-out paths are unobstructed. Another advantage is that the terrain is good for surface vehicles, and crevasse-free routes could be found to permanent building sites on adjacent nunataks. The upper part of Reedy Glacier is badly crevassed, so it would not be easy to establish a surface route to South Pole.

Site 27: Quonset Glacier (Wisconsin Range map sheet)
85°25'S, 125°30'W, elevation 1200 m (3900 ft), TMA 856 F33 184.
This site was not reconnoitered, but it is surrounded on three sides by mountains.

Site 28: Buckley Island (The Cloudmaker map sheet)
84°56'S, 164°35'E, elevation 1750 m (5700 ft), TMA 999 F33 004.
This icefield was found to have too much snow cover. Moreover, the up-glacier approach would be into high land.

Site 29: Lizard Point (The Cloudmaker map sheet)
84°49'S, 163°40'E, elevation 1800 m (5900 ft), TMA 999 F33 011.
This is a smooth flow band off a lateral moraine on the left bank of Beardmore Glacier at Lizard Point. The slope, however, evidently exceeds 2%.

Site 30: Lewis Cliff (Buckley Island map sheet)
84°15'S, 161°30'E, elevation 2000 m (6500 ft), TMA 999 F33 044.
This is a northward-flowing distributary glacier tongue from Walcott Névé and also a major meteorite collecting site intensively surveyed by Professor Cassidy's group. But its dimensions are inadequate and its slopes too steep for ice runways.

Site 31: Ramsey Glacier (The Cloudmaker map sheet)
84°51'S, 178°00'E, elevation 1250 m (4100 ft), TMA 781 F33 038.
The surface of this icefield is good but there is too much slope and the area is surrounded by high mountains.

Site 32: Adams Mountains (The Cloudmaker map sheet)
84°33'S, 167°10'E, elevation 1450 m (4800 ft), TMA 766 F33 038.
This is a 5000 x 1000 m (16,000 x 3000 ft) icefield beside a narrow string of moraine off the left bank of Beardmore Glacier below the Adams Mountains. There are a number of smooth sites on level bands between subdued steps in the longitudinal profile of the glacier. Good runways could be selected after a ground survey. There are no cracks but up to 10% snow cover underlain by smooth ice.

Site 33: Beardmore Glacier (The Cloudmaker map sheet)
84°28'S, 168°20'E, elevation 1250 m (4100 ft), TMA 775 F31 165.
This is a 5000 x 1000 m (16,000 x 3000 ft) area off a lateral moraine on the left bank of Beardmore Glacier. There are long and very smooth ice areas and some less smooth but still usable areas. Good runways could be selected after a ground survey. There are no cracks but up to 10% snow cover underlain by smooth ice.

Site 34: The Cloudmaker (The Cloudmaker map sheet)
84°23'S, 169°42'E, elevation 950 m (3100 ft), TMA 775 F33 168.
This is a 5000 x 100 m (16,000 x 300 ft) smooth flow band on the Beardmore Glacier. The surface has many transverse cracks a few inches wide but these would not be a problem for large wheeled aircraft.

Site 35: Shackleton Glacier (Shackleton Glacier map sheet)
85°00'S, 176°30'W, elevation 1000 m (3300 ft), TMA 780 F33 062.
There are a number of usable flow bands along Swithinbank Moraine but meltwater streams and ponds make the area unattractive.

Site 36: Duncan Mountains (Shackleton Glacier map sheet)
84°58'S, 166°00'W, elevation 150 m (500 ft), TMA 1009 F33 100.
This icefield was not reconnoitered, and is surrounded on three sides by mountains.

Site 37: Le Couteur Glacier (Shackleton Glacier map sheet)
84°42'S, 170°20'W, elevation 250 m (800 ft), TMA 856 F33 070.
This icefield off a lateral moraine on the right bank of Le Couteur Glacier was not reconnoitered. It appears to have >10% snow cover.

HOWE ICEFIELD

Figure 1 shows the location and Figure 2 offers a general view of the icefield, which covers an area of about 15 square kilometers (6 square miles). On the east side it is bounded by a moraine field 9 km long and 1 km wide, and on the west side by increasing snow cover and also crevasses. The northern and southern limits are represented by ice slopes exceeding 2%.

The purpose of our ground survey was to undertake some optical leveling with stadia tacheometry in order to establish typical gradients over the icefield. A topographic survey was not intended nor was time available for it. The leveling was planned only to establish whether or not a case could be made for topographic survey at a later date. Optimum runway sites should be selected on the basis of a map with contours at 0.5 m intervals.

The icefield is remarkably level, the highest point on all the lines surveyed being only 24 m (80 ft) above the lowest. Throughout the operation it was evident that the bearing strength of the surface was adequate for any type of wheeled aircraft. In fact it was not possible, except where snow lay on the ice, to follow the wheel tracks of an aircraft.

Figure 3 shows several characteristics of the icefield that were later confirmed on the ground. The long dimension of the usable area is parallel with the moraine but the prevailing wind blows across it. The smoothest and most snow-free ice lies close to the moraine but in the same area there are subdued long-wave undulations. Two of them can be seen trending westwards from the moraine in the middle of the picture. The surface further from the moraine becomes progressively smoother in terms of long-wave undulations but rougher in terms of small ice bumps, and the proportion covered by snow increases.

From the ground, however, the surface generally looks smooth and level over vast areas (Figures 4-7), and Twin Otter aircraft can safely land anywhere on wheels. It was clear that topography could only be quantified by optical leveling, so the principal survey line was set out along what appeared to be the optimum track. For convenience we refer to this as Runway 09 because approaches in the up-glacier direction are unobstructed by terrain and winds are unlikely to favor its use in direction 27. Three lines were leveled perpendicular to Runway 09 in order to quantify gradients in that direction.

Bamboo markers were drilled into the surface to control the direction of leveling profiles (Fig.8). The leveling data are listed in Appendixes 1 and 2 and summarized in a sketch map (Fig. 9). Our camp was at Flag 9, and only after profiling Runway 09 did it become clear that the tents were in a subdued east-west trending depression. The Howe Valley Line (Appendix 2) was profiled to determine how far west this valley extended.

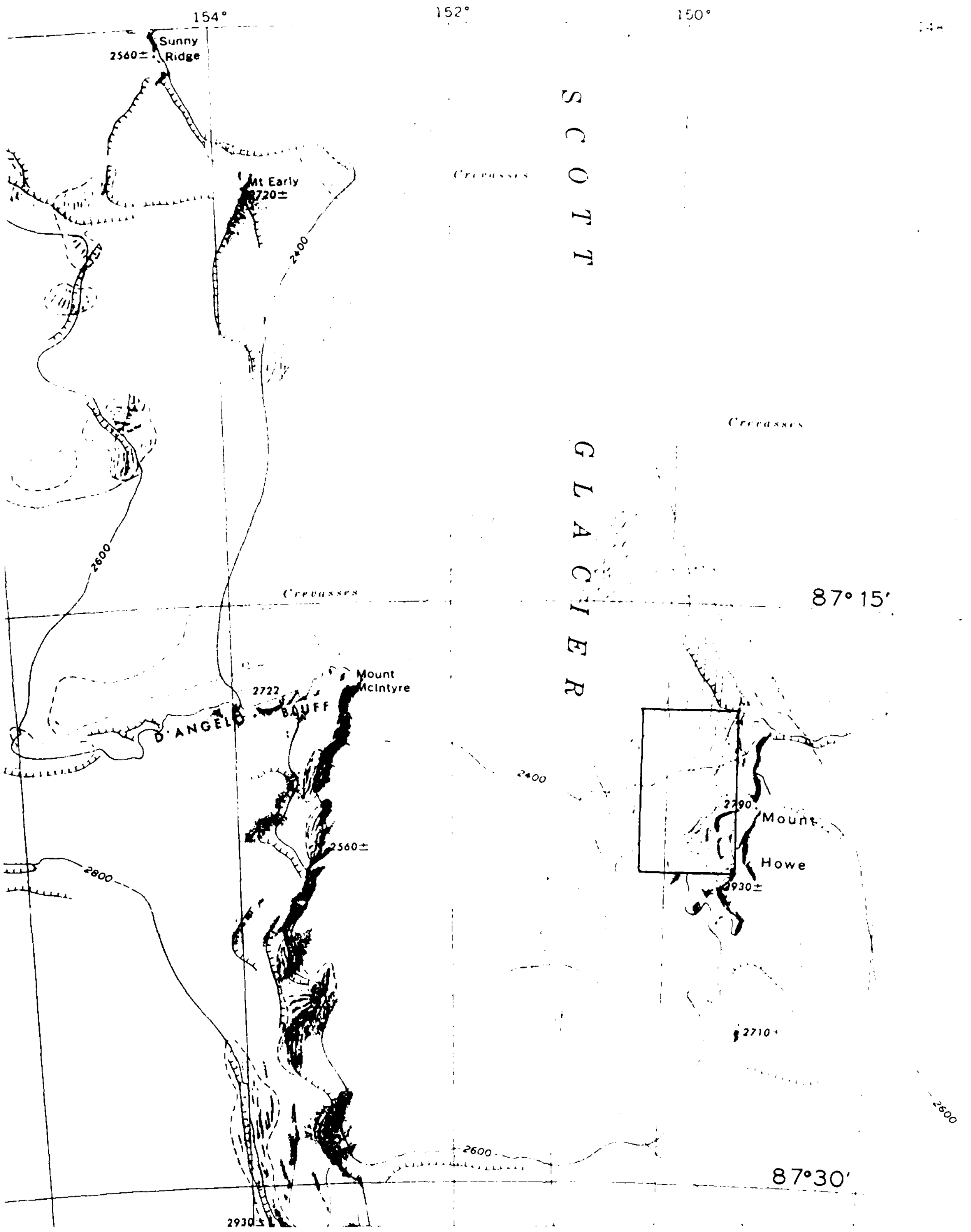

Figure 1. Portion of D'Angelo Bluff map sheet, scale 1:250,000. Inset shows area covered by Figures 8 and 9.

Figure 2. The icefield at Mount Howe (center). Oblique aerial photograph taken from an altitude of 7300 m (24,000 feet) on 9 December 1961 facing towards the South Pole. Photo: US Navy for US Geological Survey (TMA 891 F33 106).

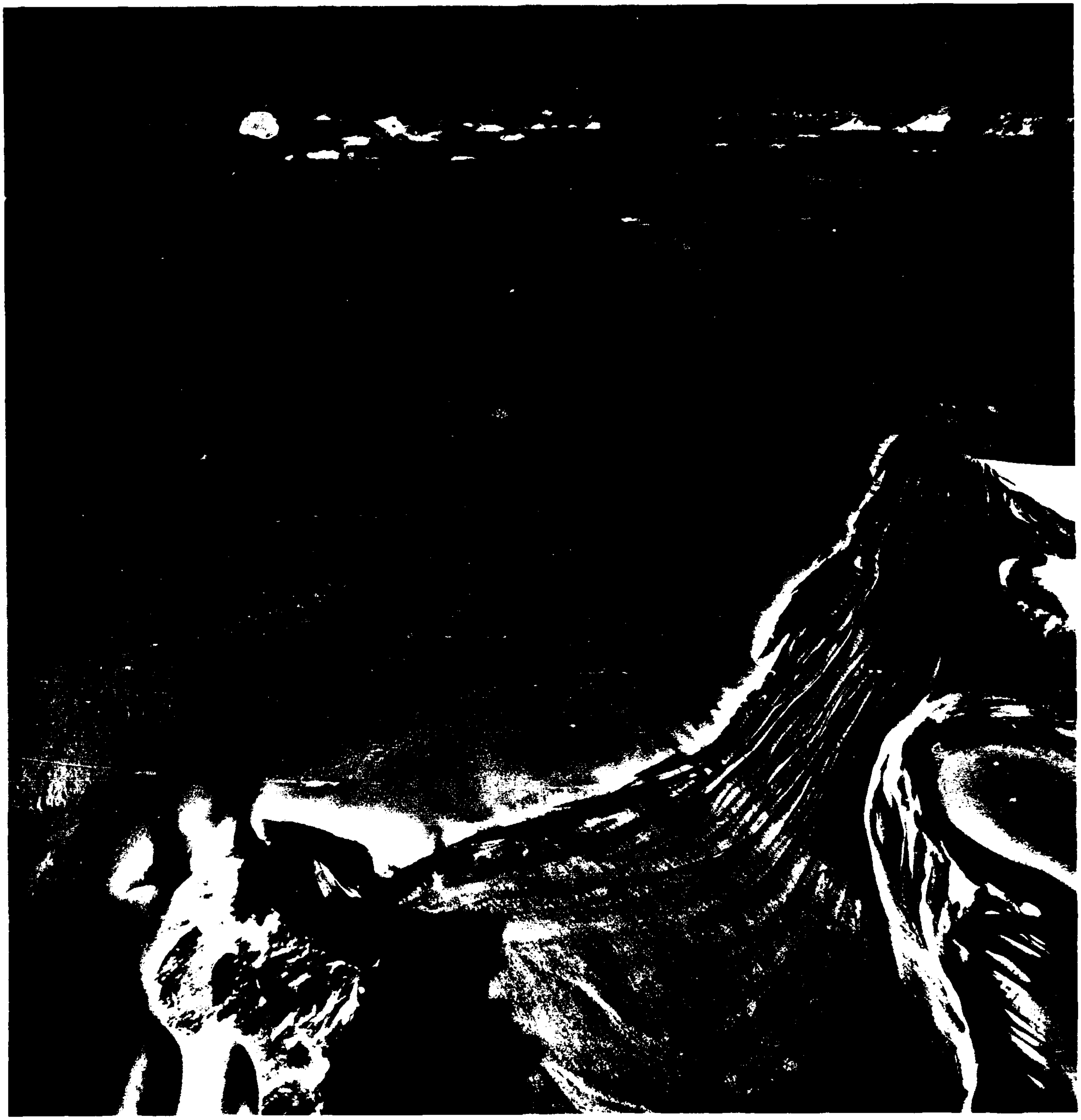

Figure 3. The icefield at Mount Howe (center). Oblique aerial photograph taken from an altitude of 5700 m (19,000 feet) on 31 October 1963 facing 342° true. Photo: US Navy for US Geological Survey (TMA 1203 F31 045).

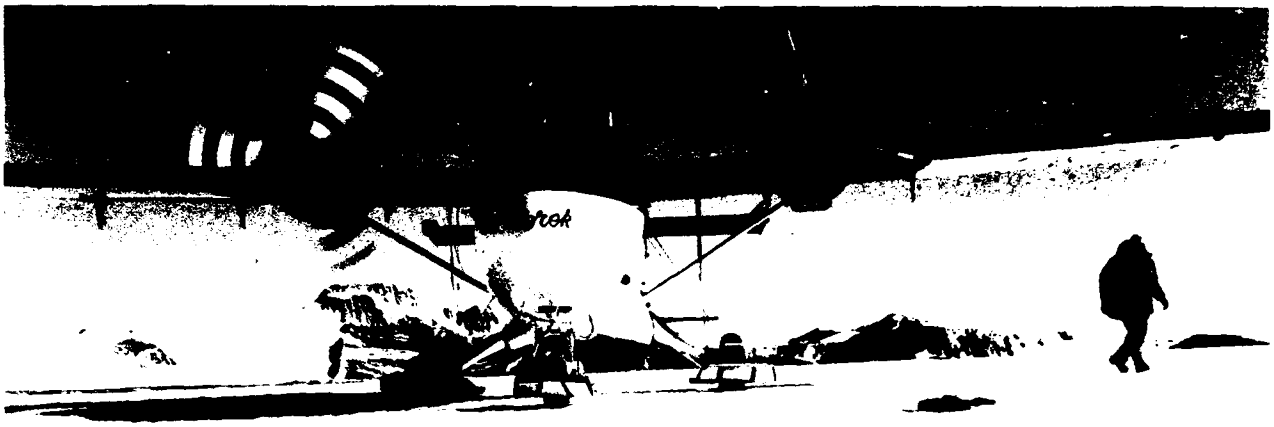

Figure 4. Wheel landing on Howe icefield, 10 December 1988. The camera faces south. Mount Howe (2930 m, 9600 ft) is under the starboard engine. Note wind-borne moraine fragments on surface.

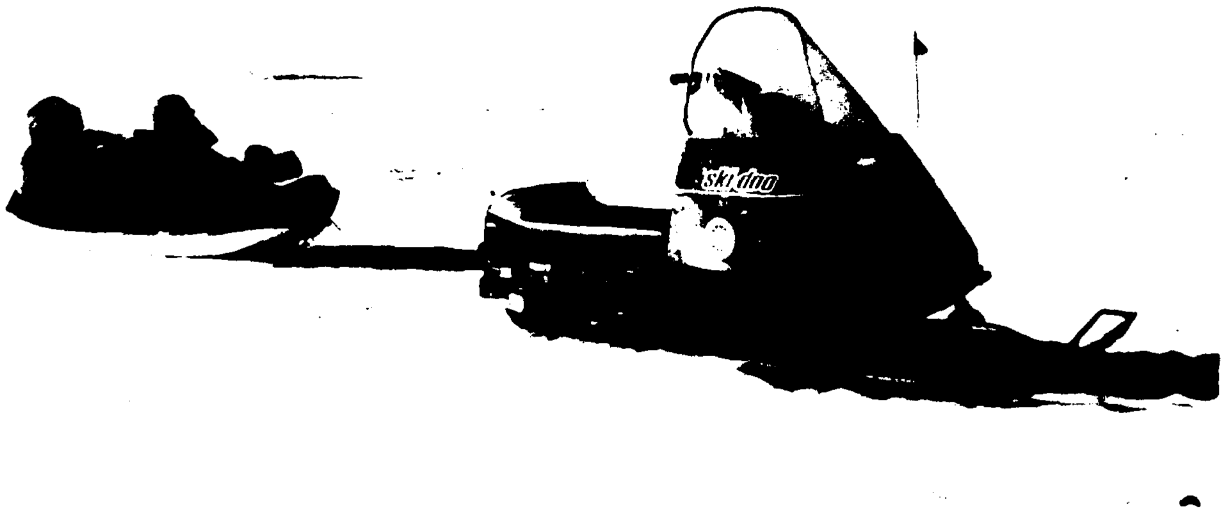

Figure 5. Bone-shaking travel on the icefield. The camera faces WNW. Note sastrugi increasing towards D'Angelo Bluff (left center).

Figure 6. Howe icefield with the camera facing SSW. Runway 09 is directed at the dark bluff just to the right of the pilots.

Figure 7. Howe icefield with the camera facing NNE from the same place as Figure 6. The northern end of the moraine field can be seen (right).

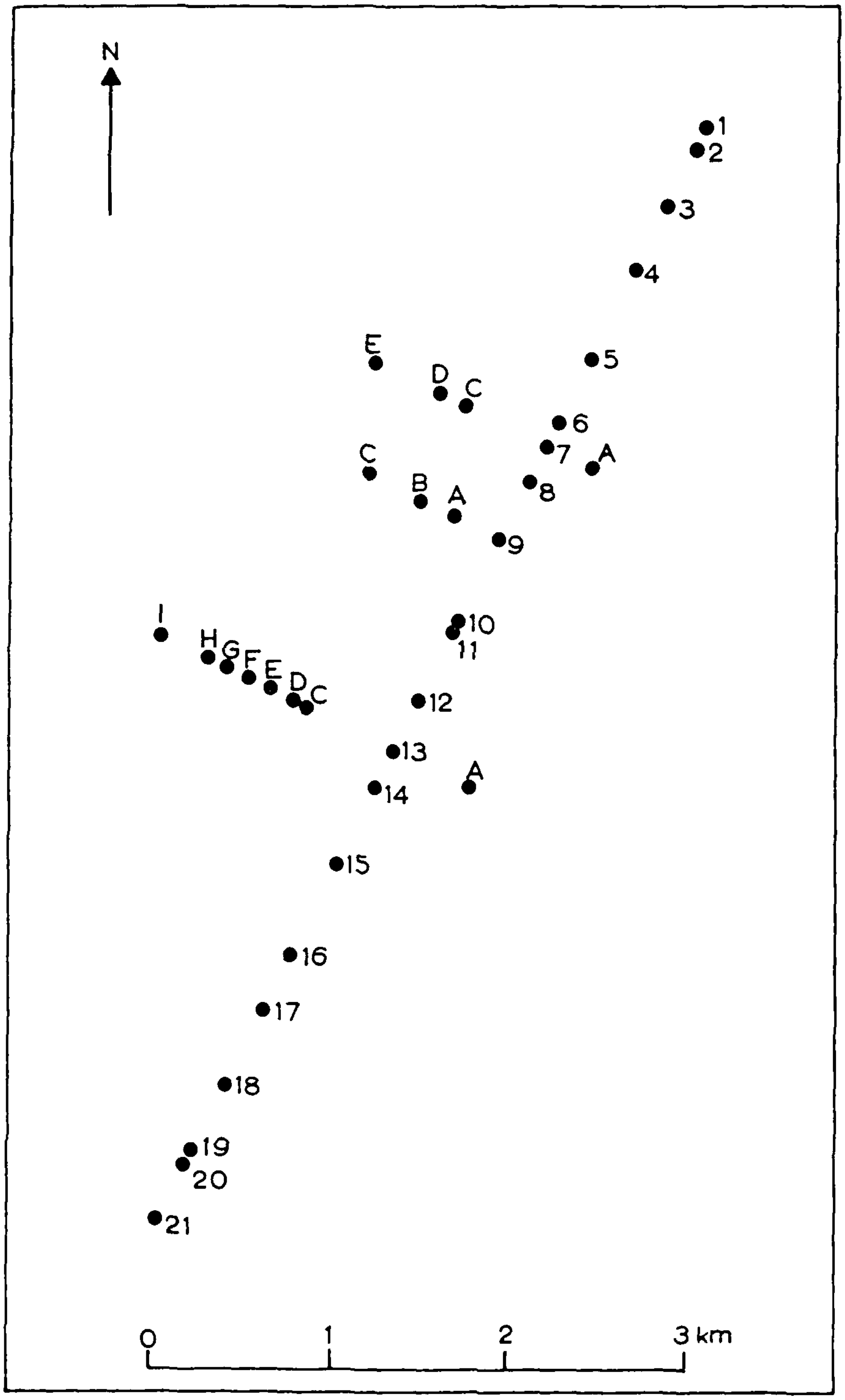

Figure 8. Location of bamboo markers set up to guide Howe icefield leveling survey. Each marker is numbered in pencil and topped with a green flag.

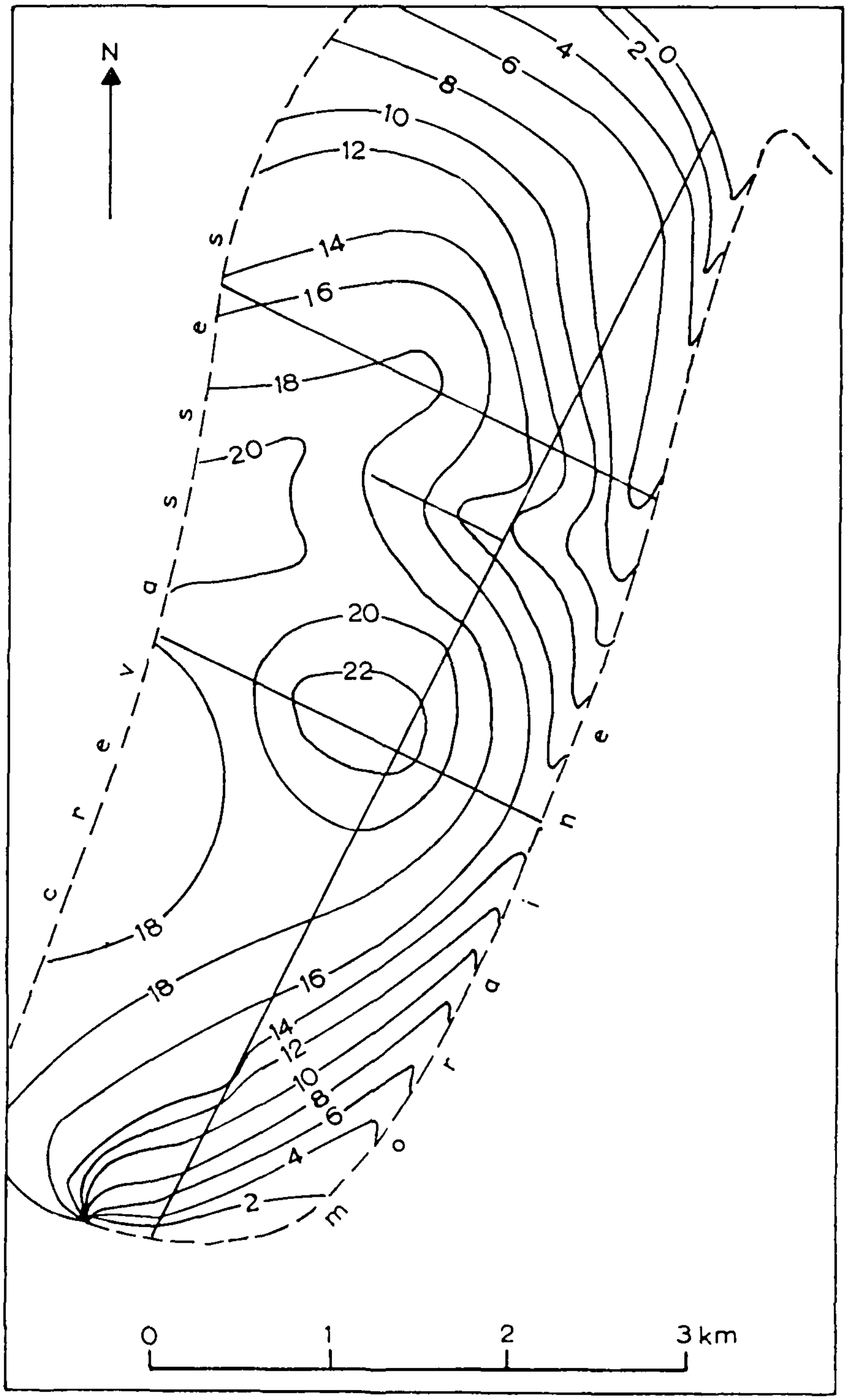

Figure 9. Sketch map of Howe icefield covering the same area as Figure 8. Form lines at 2 m (6.6 ft) intervals are conjectural except where surveyed along the four straight lines. Elevations refer to an arbitrary datum at the threshold end of Runway 09 (Fig.10).

Figure 10 shows the longitudinal profile of Runway 09. Gradients over most of its length are well under 1% and only locally approach 2% for a short distance near the Flag 9 valley (from 2.8 km to 3.0 km). The section from 3.3 km to 6.3 km defines a 3000 m (10,000 ft) runway with an overall mean gradient of only 0.3% and a maximum gradient at any point along it of 0.5%. Transverse gradients were not surveyed but throughout this section appear to be under 1%.

Figure 11 shows the profile of Howe Cross Line through Flag 7. Approached from the west as Runway 36L, the section from 2.64 km to Flag 7 (at 0.67 km) defines a 1970 m (6460 ft) runway with a mean gradient of 0% and a maximum gradient at any point along it of 0.8%. The shorter length available in this direction would be offset by its alignment into the prevailing wind.

Figure 12 shows the profile of Howe Cross Line through Flag 13. Approached from the west as Runway 36R, the section from 2.31 km to 0.71 km defines another into-wind runway 1600 m (5250 ft) long with a mean gradient of 0.2% and a maximum gradient at any point along it of 1%.

Figure 13 shows the profile of Howe Valley Line from Flag 9. This indicates that the valley in which the camp was situated does in fact peter out 800 m to the west.

Given that the form lines in Figure 9 may be approximately correct, it now appears that Runway 09 could with advantage be displaced 800 m (2600 ft) to the west. This could potentially yield a 7000 m (23,000 ft) profile that at no point exceeded a longitudinal (or transverse) gradient of 1%. Another advantage would be an easier climb-out path passing to the right of the rock bluff that is seen behind the pilots in Figure 6. The distant ice horizon would permit a climb-out path as low as 1° from Flag 6. Moreover it would avoid the downslope towards the moraine that shortens the usable portion of the surveyed profile by some 500 m (Fig.10).

Possible runway alignments are in no way limited to those surveyed, though Runway 09 is the only practical direction that does not face rising terrain. Figure 9 shows that another low-gradient long runway could be aligned N-S (180°true) passing through the 22 m summit of the icefield. This runway, as also Runways 09, 36L and 36R, would have totally unobstructed approach paths allowing glide angles as low as 1°. Climb-out angles to clear rising terrain, however, would typically be around 5° in contrast to the 1° climb-out from Runway 09.

We conclude that runways aligned roughly with the long dimension of the icefield will be preferred except at times when the crosswind component exceeds safe limits for the aircraft type. Under high wind conditions it is probable that the available into-wind runways would be of adequate length.

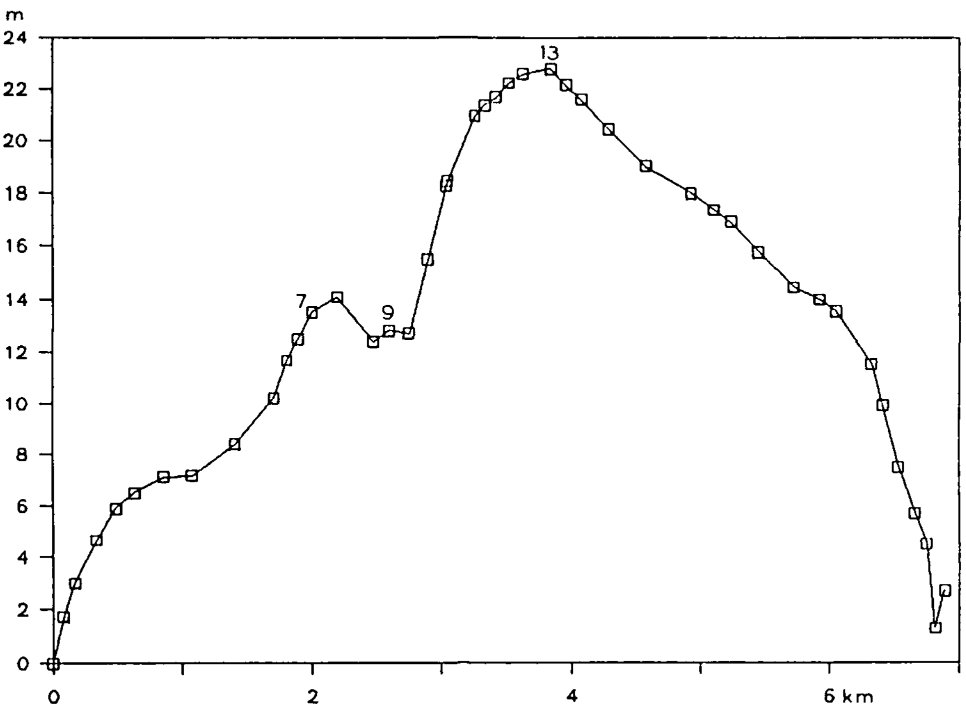

Figure 10. Profile of Howe Runway 09 (207°true, 057°grid) from its threshold (left) to the moraine at its southern extremity. Flag numbers show the positions of the three perpendicular leveling surveys.

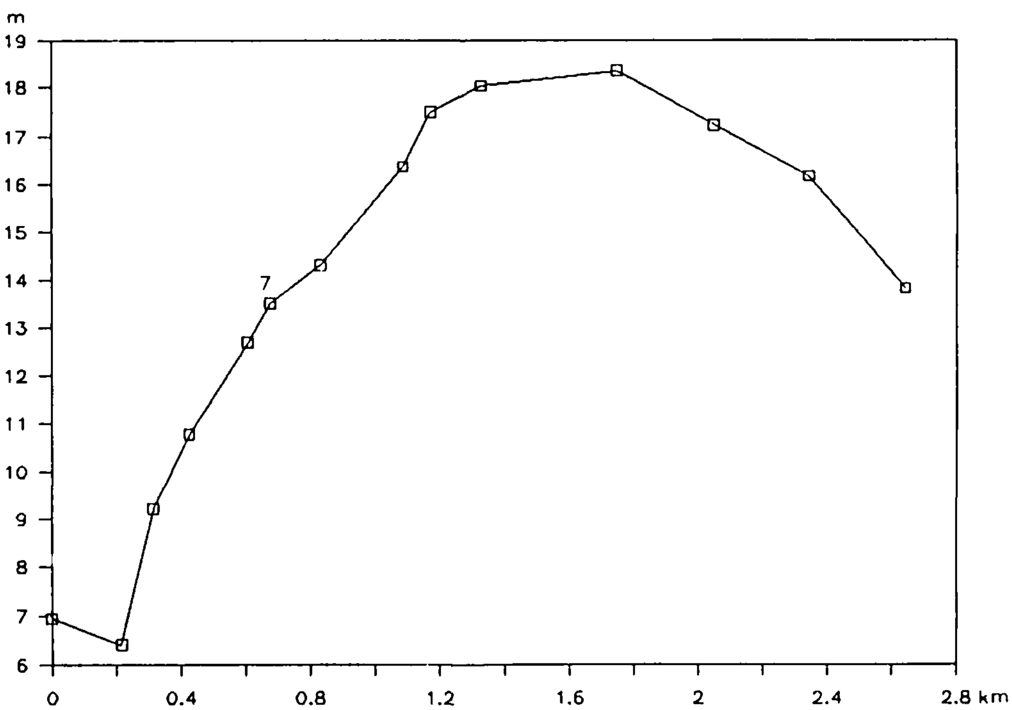

Figure 11. Profile of Howe Cross Line through Flag 7 (180° magnetic, 297° true, 147° grid) from the edge of moraine (left).

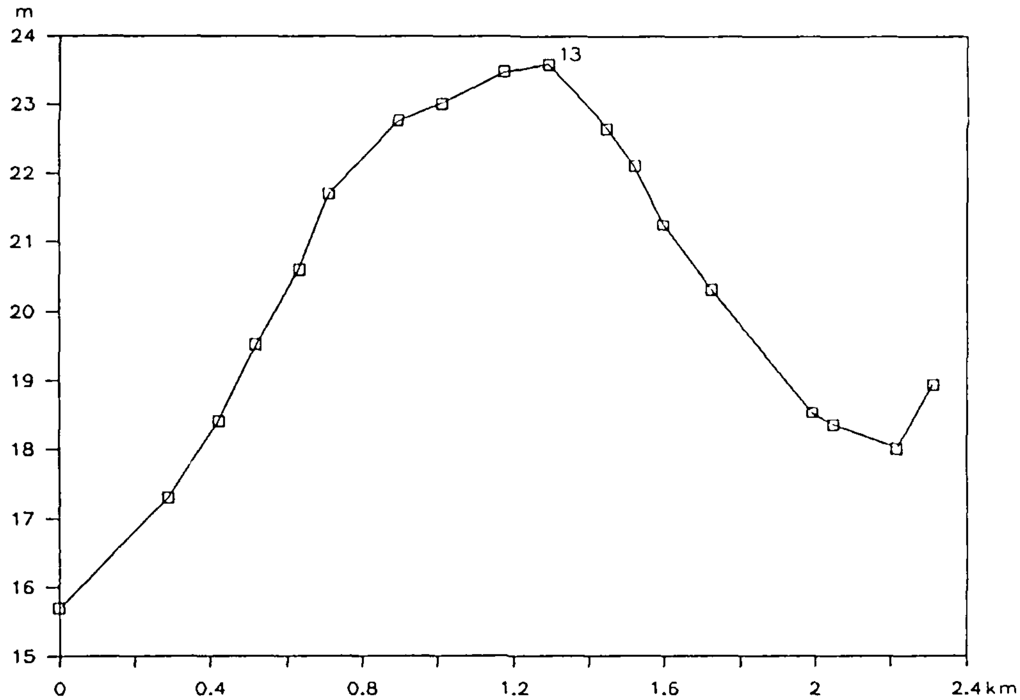

Figure 12. Profile of Howe Cross Line through Flag 13 (180° magnetic, 297° true, 147° grid) from the edge of moraine (left).

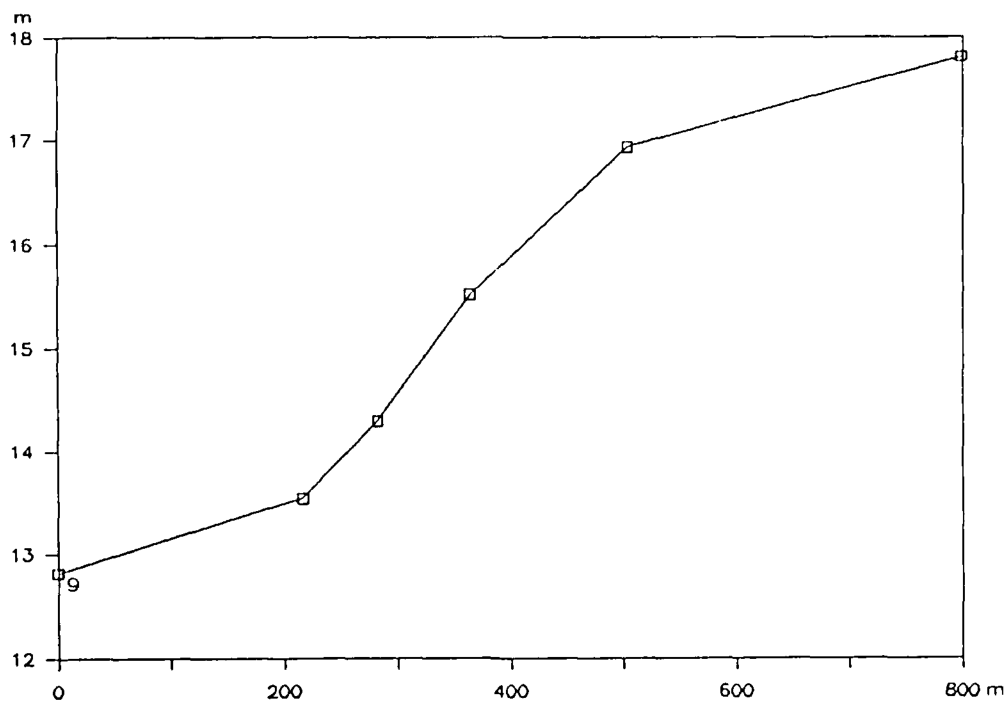

Figure 13. Profile of Howe Valley Line from Flag 9 (180° magnetic, 297° true, 147° grid).

Small-scale surface features

Sastrugi. There are no sastrugi within the first 500 m (1600 ft) from the moraine but beyond that there are isolated patches covering between 1% and 5% of the surface. As far as about 1500 m (5000 ft), however, they are of little practical significance for aircraft operations on wheels, in that the snow is soft and overlies hard ice (Figs.4-7) with the same characteristics as elsewhere. They could easily be removed with conventional snow-blowing equipment. Beyond about 1500 m (5000 ft) from the moraine, some of the sastrugi evidently stop migrating and begin to recrystallize into what we may call ice bumps. These are of significance for aircraft.

Ice bumps. Significant ice bumps (>10 cm or 4 inches in height), not necessarily derived from sastrugi, begin to appear about 500 m from the moraine and progressively increase in height to a maximum of about 30 cm (12 inches) at the western extremity of the icefield. It was not possible to quantify the varying size of these features over the whole icefield but we did make a sample survey in two directions from Flag 11 on Runway 09 (Figs.14 and 15; Appendix 3). Our conclusion was that some form of planing machinery must be used before a runway can be considered safe for use by large transport aircraft. We do not believe that planing would involve difficult engineering problems.

Suncups. This word is used to describe the ubiquitous surface microrelief seen in Figs.4-7. Suncups are probably caused by turbulence in the boundary layer of air passing over the icefield and its effect on sublimation. They may also serve to focus the incident solar radiation and affect sublimation in that way. Howe icefield suncups are generally about 5 cm (2 inches) deep but exceptionally 10 cm (4 inches). They are appreciated by pilots because they facilitate wheel braking. Indeed pilots report being able to hold aircraft stationary while applying >50% power.

Crevasses. There are no crevasses on the icefield except along its western boundary. Crevasses 30 cm (12 inches) wide mark the threshold of Runways 36L and 36R. Either of these runways could be extended some distance westwards by filling the small crevasses by means of planing machinery.

Rocks. Widely-spaced rock fragments are scattered about the ice surface, evidently transported by wind from the moraine field. Pieces are typically around 50 g but range up to about 100 g (3 oz). Dimensions are in the range 25-75 mm (1-3 inches). One iron meteorite 100 mm (4 inches) in length and weighing 2.5 kg (5.5 lb) was found, but these are very rare and highly valued by scientists. There was no sign of the rocks sinking into the ice under the influence of solar radiation. They are unlikely to affect aircraft operations or to cause problems for ice-planing machinery.

Weather

Prevailing winds varied little from 120°true throughout out stay on the icefield, and the orientation of sastrugi suggested that this was normal. Wind speeds averaged around 10 knots. We had one calm day and one day with winds up to 30 knots. Temperatures averaged -20°C (-4°F).

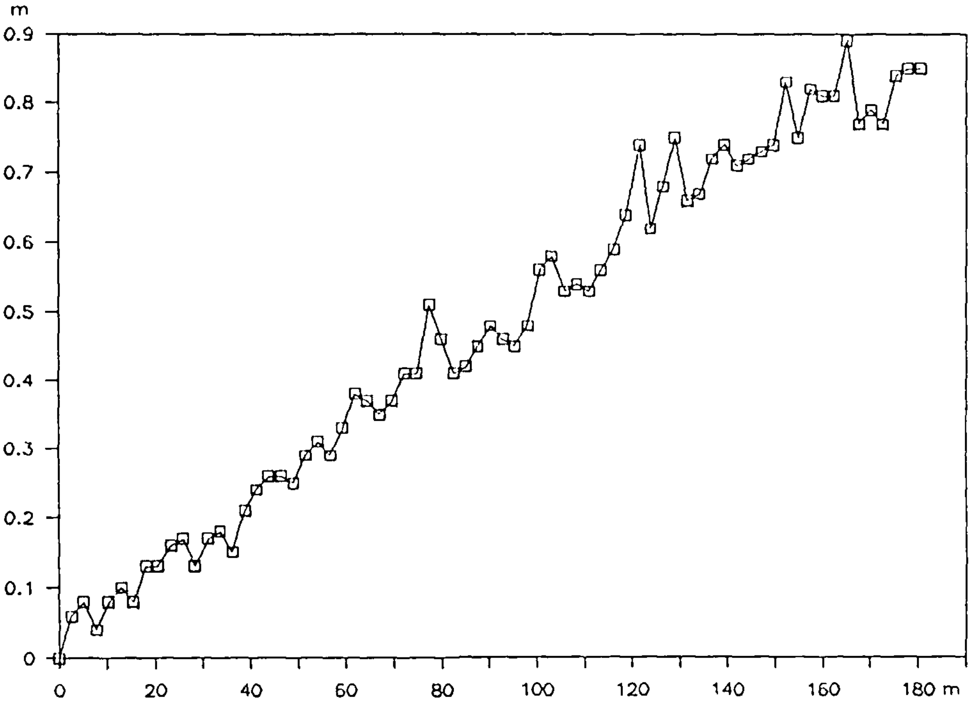

Figure 14. Howe Microrelief Profile along Runway 09 from Flag 11.

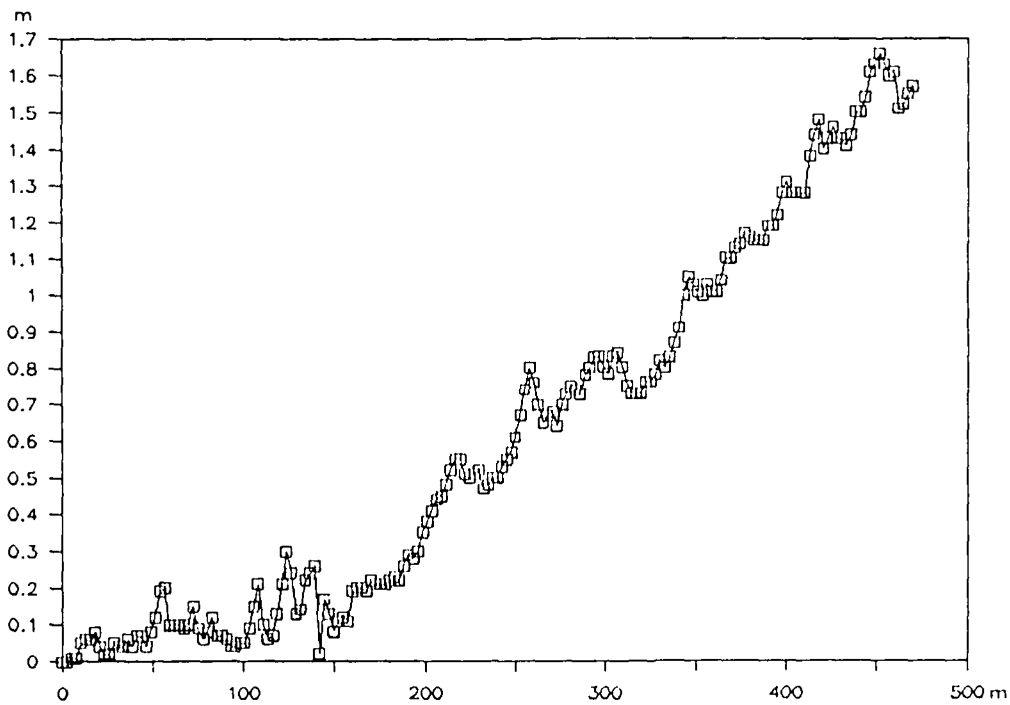

Figure 15. Howe Microrelief Profile along 180° magnetic from Flag 11.

Overland route to South Pole

We feel confident that a crevasse-free overland route to the South Pole could be established. Starting from the icefield, the route would stay close to the rock ridge (Fig.2) until south of Mount Howe, then cross the icefield beside Point 2710 (Fig.1), the world's southernmost nunatak (above Mount Howe in Fig.2). From here the route would head for 87°30'S, 148°W and thence due south. Although there are scattered patches of severe crevassing between here and 87°47'S, there are mile-wide spaces between them. The best way to establish a trail would be with a lightweight oversnow vehicle and a Twin Otter in attendance overhead to comment on the proximity of crevasses. From 87°50'S to the South Pole the route should be easy and no aircraft would be needed.

Operation of ski-equipped aircraft

There remains the problem of how to bring in ice-planing equipment to make the icefield safe for transport aircraft on wheels. This could be done overland from South Pole. Alternatively LC-130 aircraft could land on snow closer to Mount Howe if the surface was suffiently smooth. We cannot recommend ski landings close to Mount Howe because the sastrugi appeared substantial and hard, but it is likely that an acceptable surface could be found by further reconnaissance. We did identify an area with almost no sastrugi around 88°45'S, 150°W, that would provide an excellent surface for ski landings of LC-130 type aircraft. Tracked vehicles brought this far could make their own way overland to Howe icefield.

Surface mass balance

Although we expect the net mass balance to be slightly negative over most of the area of the icefield, meaning that the surface is eroded by sublimation at a rate of perhaps 2-5 cm/yr (1-2 in/yr), for practical purposes we need to know what the actual rate is. We measured the exposed length of each marker stake from the ice surface to the top of the stake, and it is important that each stake should be remeasured during the 1989-90 season to determine the net mass balance over the interval. Some of the stakes will be broken or missing after winter storms, so they must be carefully identified, either by reading the small hand-written number or alternatively by determining their position relative to neighboring stakes (Fig.8). Anomalous results at a single stake are more likely to be due to the stake having settled or melted its way down through drill chippings than to any real local effect. The results of our measurements are shown in Table 1.

Table 1 Exposed height of stakes on 28 December 1988

Flag	Height (cm)	Flag	Height (cm)
1	150	13	153
2	148	13A	150
3	160	13B	147
4	147	13C	150
5	149	13D	148
6	149	13E	143
7	146	13F	161
8	158	13G	147
9	145	13H	155
9A	147	14	148
9C	148	15	153
10	149	16	147
11	155	17	163
12	145		

Trafficability

The best way to move about on the icefield is with conventional transport on wheels, not track-laying vehicles. Whether on wheels or tracks, LGP versions are not needed. There is more than one reason to avoid track-laying vehicles except where extreme draw-bar pull is required. Tracked vehicles can damage the brittle surface of the icefield and they leave more behind in the form of oil and grease. In contrast to South Pole, nothing left on the icefield will be concealed by snow; in a hundred years' time it will still be visible on the surface. Or worse, it can cause a glacier table (raised pedestal) or a cryoconite hole (possibly water-filled). Immense care must be taken to remove any kind of artifact or debris from the surface. In this connection, empty fuel drums should not be used as runway markers. Runway markers should be held clear of the surface (as they are at South Pole) on uprights as small in their cross sectional area as practicable.

Construction

The moraine field rests on glacier ice, but there is enough material in the form of boulders and rock fragments of every size to provide platforms to support a city. No bedrock sites are available close alongside the icefield, but exposed bedrock sites 100 m (300 ft) or more above the icefield are available on the rock ridge that forms the southern boundary of the moraine field. Buildings can be erected on the icefield but over a period of years they would progressively appear to be raised up on a pedestal. Eventually they would fall off their pedestal.

MILL ICEFIELD

Figure 16 shows the location and Figure 17 offers a general view of part of the icefield, which covers an area of more than 20 square kilometers (8 square miles). On the west side it is bounded by Plunket Point and Meyer Desert, and on the east by giant rifts. To the north it is bounded by the Plunket Point medial moraine and to the south by crevasses.

The smoothest band of ice is aligned in the direction of glacier flow and also (in contrast to Howe icefield) in the direction of the prevailing wind. As with the earlier survey, leveling was planned only to establish whether or not a case could be made for topographic survey at a later date. Throughout the operation it was evident that the bearing strength of the surface was adequate for any type of wheeled aircraft. In fact it was not possible to follow the wheel tracks of an aircraft.

From the ground, the surface looks smooth over vast areas (Figures 18-21). A longitudinal survey line was set out along what appeared to be the optimum runway alignment. For convenience we refer to this as Runway 36 because approaches in the up-glacier direction are unobstructed by terrain and prevailing winds favor its use in that direction. Glide angles as low as 1° could be used on approach, and an angle of climb of 1° would clear terrain at the far end. The down-glacier approach (as Runway 18) is also unobstructed but it would involve a down-wind and downhill landing. Runway 18 would, however, be used for take-off in calm wind conditions. Although our preliminary runway site may yield to a slightly different alignment based on topographic mapping, it is good as it stands and suitable for any type of wheeled aircraft.

Bamboo markers were drilled into the surface to control the direction of leveling profiles (Fig.22). Two lines were leveled perpendicular to Runway 36 in order to quantify gradients in that direction. The leveling data are listed in Appendixes 4 and 5 and summarized in a sketch map (Fig.23). Our camp was at Flag 6C.

Figure 24 shows the longitudinal profile of Runway 36. The section from 0.1 km to 5.1 km defines a 5000 m (16,000 ft) strip which, although sloping at 1.3%, has neither the ice bumps nor the significant grade changes that were found on Howe icefield. Transverse gradients were not surveyed but throughout this section appear to be under 1%.

Figure 25 shows the profile of Mill Cross Line through Flag 6. There is no point in having a runway in this direction because it trends across the prevailing wind and is obstructed by terrain (Plunket Point). Runway 36 would cross it just to the right of Flag 6, where the gradient is 0.6%.

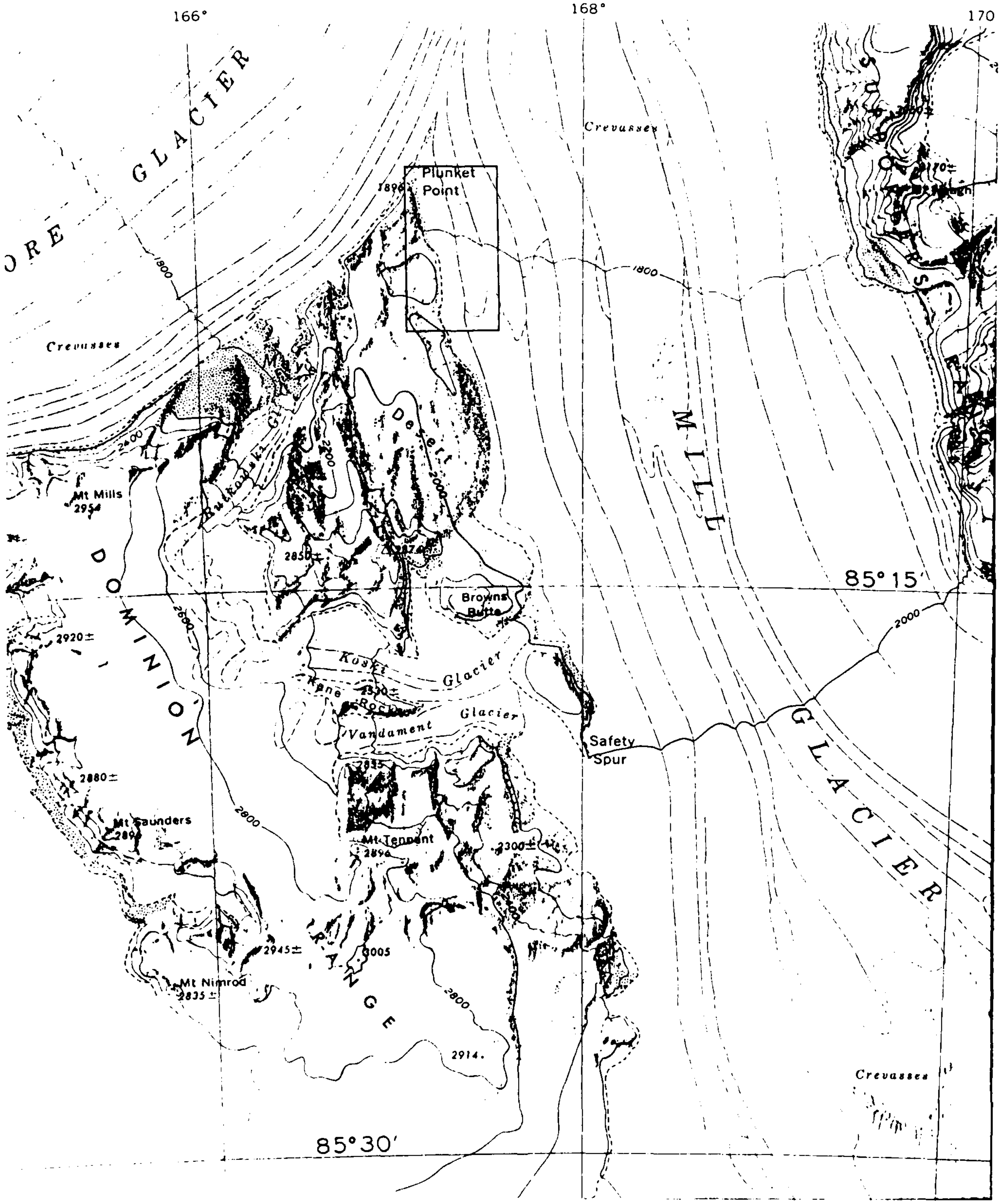

Figure 16. Portion of Plunket Point map sheet, scale 1:250,000. Inset shows area covered by Figures 22 and 23.

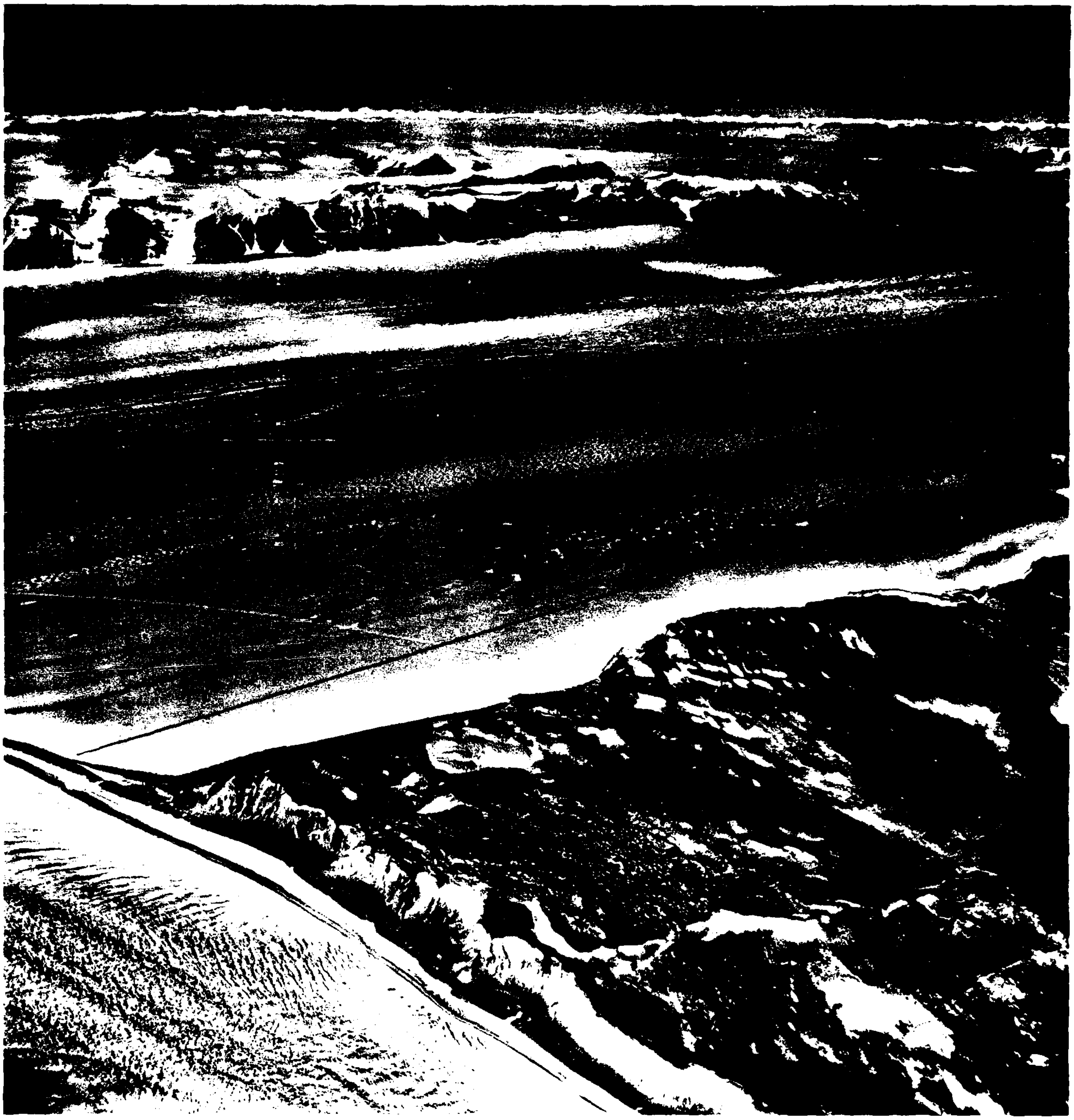

Figure 17. The icefield on Mill Glacier. Oblique aerial photograph taken from an altitude of 5700 m (19,000 feet) on 17 November 1960 facing 097° true. Runway 36 is shown as a black line. Photo: US Navy for US Geological Survey (TMA 776 F31 315).

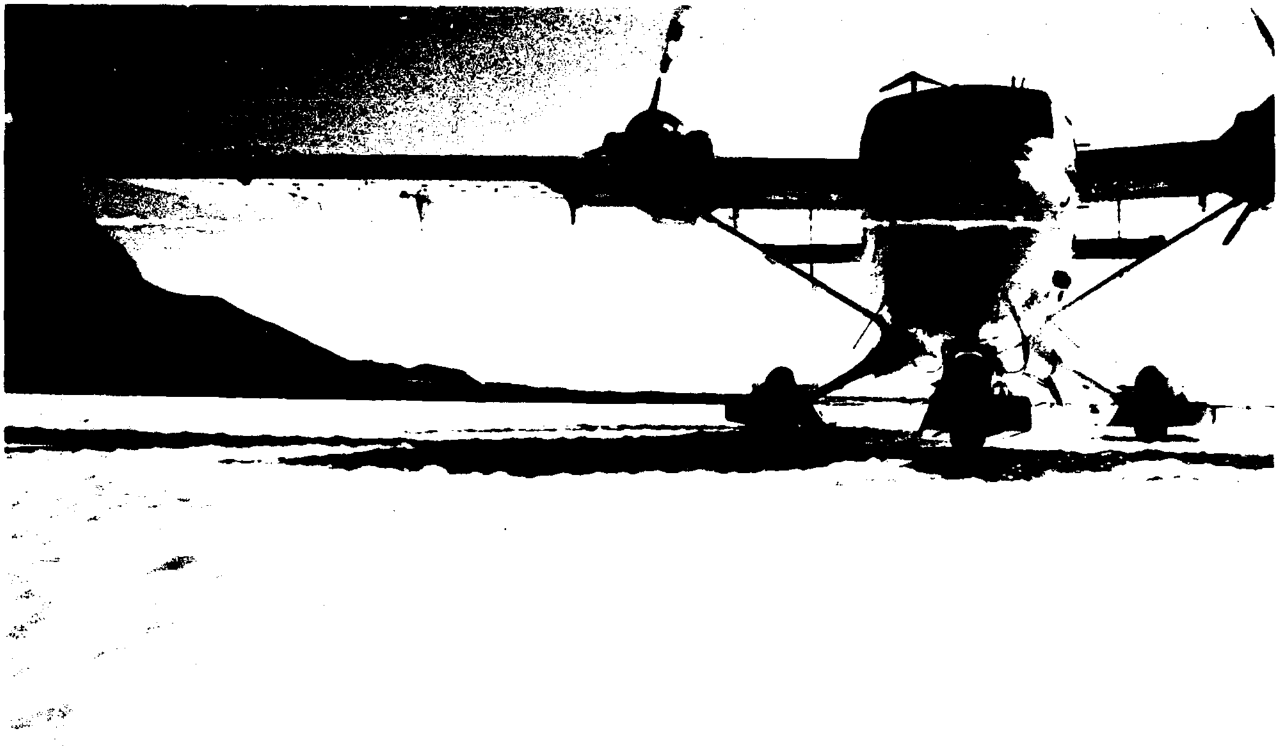

Figure 18. Wheel landing on Mill Glacier, 2 January 1989. The camera faces north-west. Plunket Point is on the left of the picture.

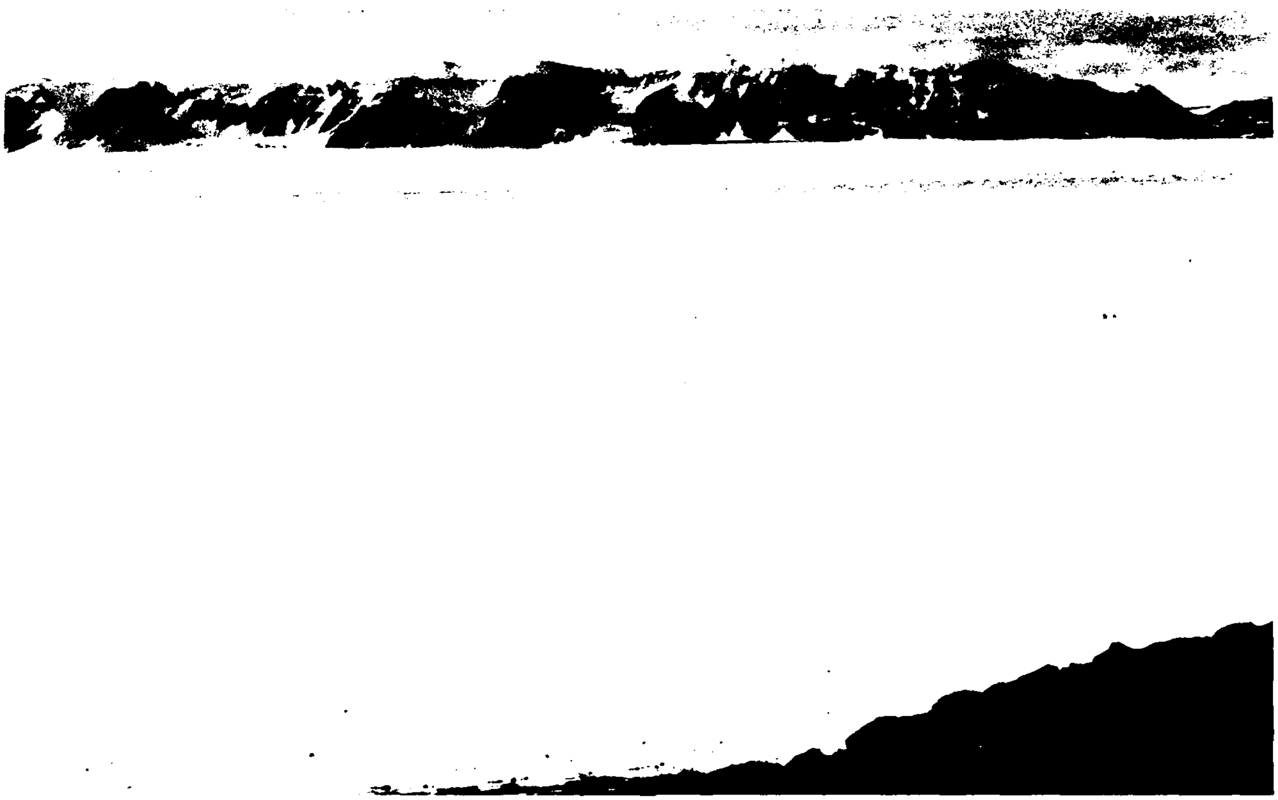

Figure 19. Looking across Mill Glacier from Plunket Point, 9 January 1989. The far side of the glacier is 21 km (11 nm) from the camera, which faces 077° true. Note tents (right). Mill Runway 36 extends across the picture from left to right, parallel with the dirt bands and 300 m (1000 ft) toward the camera from the camp. The dirt bands are imperceptible to the eye at ground level and have no surface expression.

Figure 20. Looking towards Plunket Point medial moraine from near Flag 5. Runway 36 is aligned on a reciprocal bearing from Mount Falla, which is dimly seen behind the green flag just to the right of the tripod.

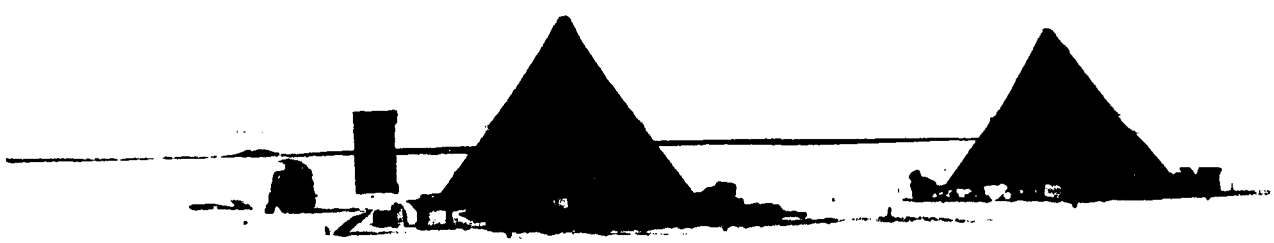

Figure 21. Camp on Mill Icefield, facing 330° true. Beyond the Plunket Point medial moraine, the far side of Beardmore Glacier is 48 km (26 nm) from the camera. The overhead contrail is a reminder that the icefield is on the direct route from McMurdo to South Pole.

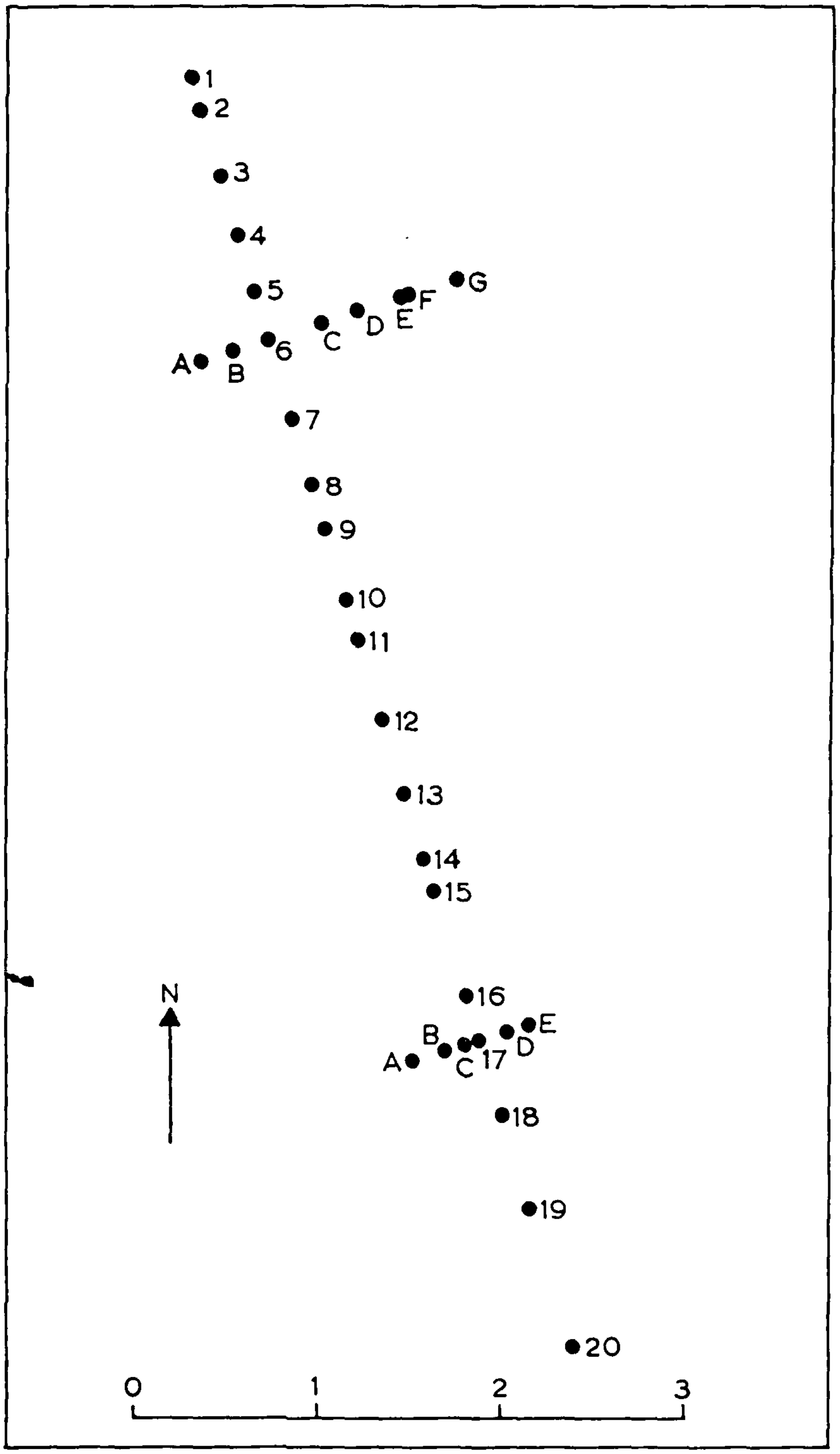

Figure 22. Location of bamboo markers set up to guide Mill icefield leveling survey. Each marker is numbered in pencil and topped with a green flag.

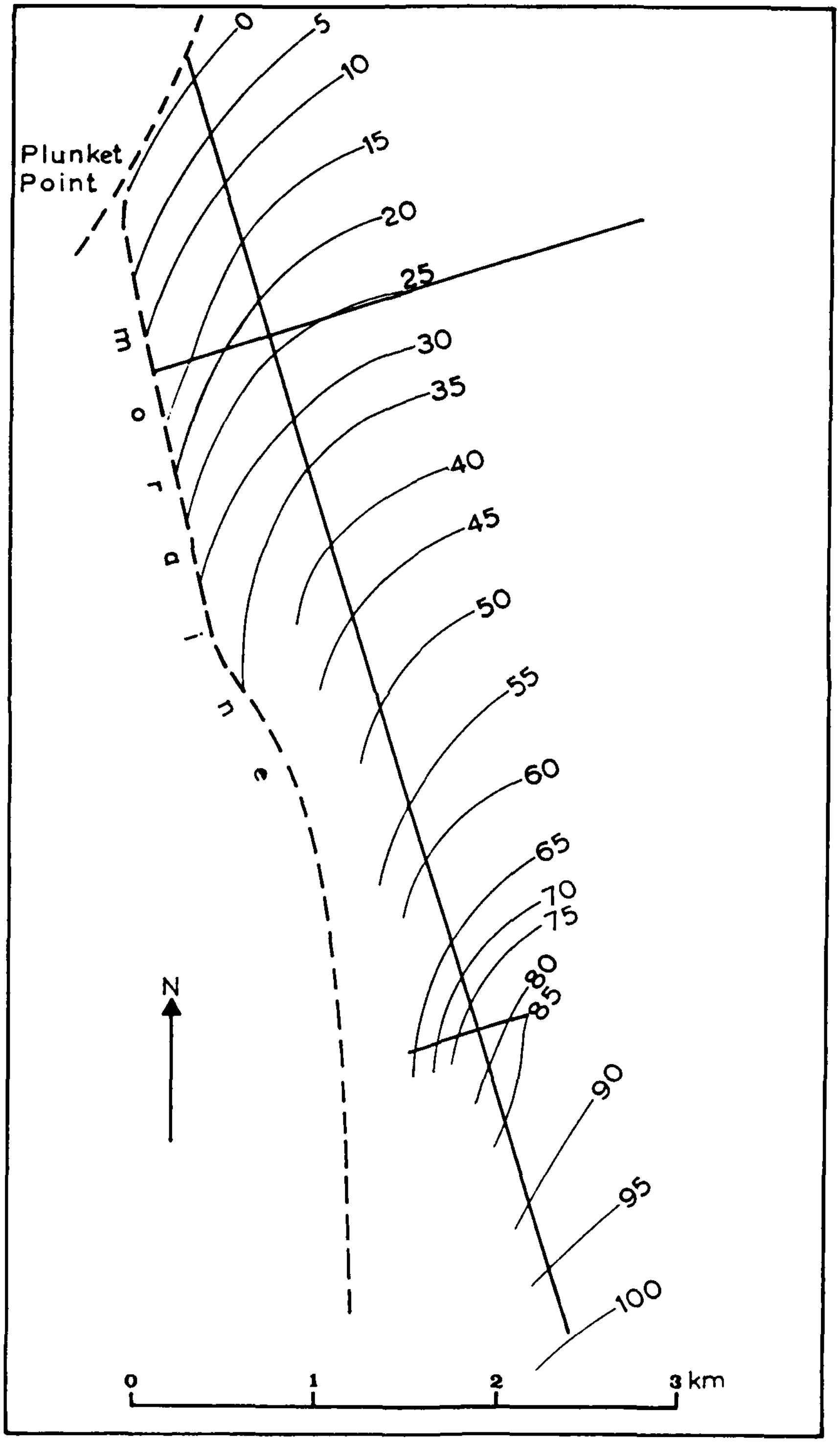

Figure 23. Sketch map of Mill icefield covering the same area as Figure 22. Form lines at 5 m (16 ft) intervals are conjectural except where surveyed along the three straight lines. Elevations refer to an arbitrary datum at the threshold end of Runway 36.

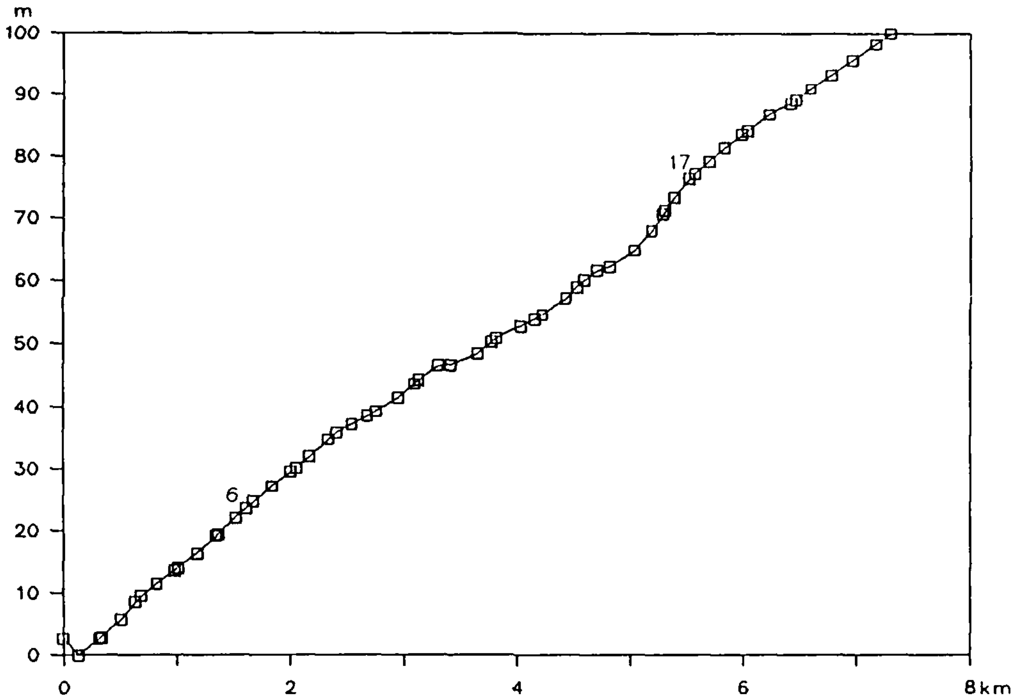

Figure 24. Profile of Mill Runway 36 (003° magnetic, 163° true, 329° grid) from its threshold (left) to where crevasses begin. Flag numbers show the position of the two perpendicular leveling surveys.

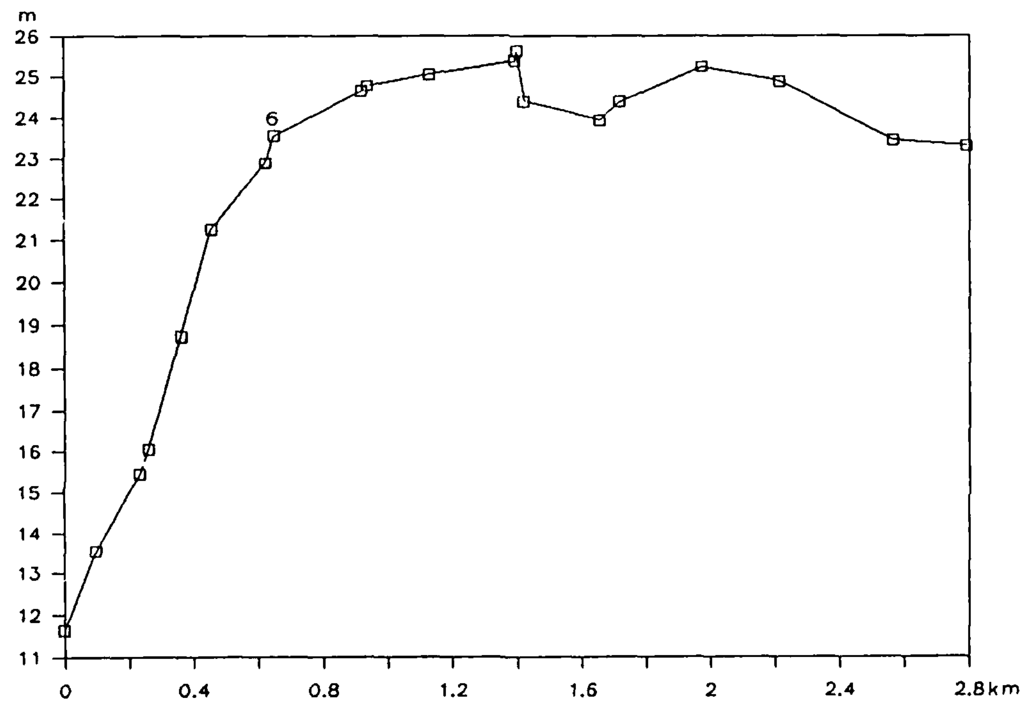

Figure 25. Profile of Mill Cross Line through Flag 6 (268° magnetic, 068° true, 234° grid) from the edge of moraine (left).

Figure 26 shows the profile of Mill Cross Line through Flag 17. The purpose of this line was to show that at this point Runway 36 is constrained by a steep slope (from 0 m to 300 m) on one side and by a giant rift at 650 m. In the unlikely event that anyone should need the full 7300 m (24,000 ft) of Runway 36, it would cross just to the right of Flag 17, where the gradient is 1.2%.

Small-scale surface features

Sastrugi. Sastrugi cover less than 1% of Runway 36 and are of little practical significance for aircraft operations on wheels. They are migrating, soft, and underlain by hard ice with the same characteristics as elsewhere. They could easily be removed with conventional snow-blowing equipment.

Ice bumps. Microrelief over the whole area is much more subdued than on Howe icefield and in our opinion does not require mechanical planing in order to prepare the surface for large transport aircraft. This does not imply that it cannot be improved by planing.

Suncups. Suncups cover the whole area (Figs. 18, 20, and 21) and are of about the same depth as those on Howe icefield. As elsewhere, they represent a distinct advantage for aircraft operations in that they facilitate wheel braking.

Crevasses. There are no crevasses on the icefield except at its southern end. Crevasses are not associated with the giant rifts that limit the icefield on its eastern side.

Weather

Prevailing winds varied little from 160°true throughout our stay on the icefield, and the orientation of sastrugi suggested that this was normal. Wind speeds averaged around 10 knots. We had one calm day and one day with winds up to 30 knots. Temperatures averaged -10°C (+14°F).

Overland route to South Pole

We feel confident that a crevasse-free overland route to the South Pole could be established. Starting from the upper end of Runway 36, the route runs along the smooth ice strip that separates Meyer Desert from the Mill Glacier crevasses. Continuing past Safety Spur, the route hugs close to the rock as far as 85°28'S. From here it proceeds in a straight line to 85°36'S, 168°04'E. The section between 85°00'S and this position is potentially hazardous owing to crevasses, but it looks as if a route could be found between them. From the north-eastern extremity of the Mount Ward ridge, the route trends about 205°true as far as 85°45'S, thence due south. Patches of crevasses may be encountered further south but they could be easily circumnavigated.

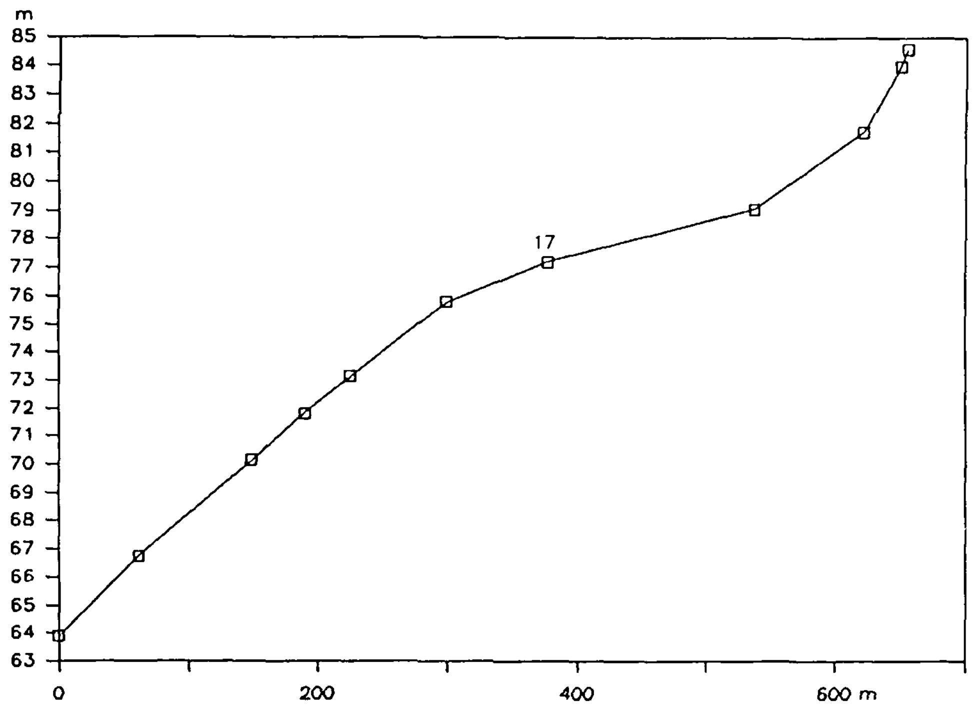

Figure 26. Profile of Mill Cross Line through Flag 17 (273° magnetic, 073° true, 239° grid) from ice slope leading down towards the edge of moraine (left).

Surface mass balance

Although we expect the net mass balance to be slightly negative over most of the area of the icefield, meaning that the surface is eroded by sublimation at a rate of perhaps 2-5 cm/yr (1-2 in/yr), for practical purposes we need to know what the actual rate is. We measured the exposed length of each marker stake from the ice surface to the top of the stake, and it is important that each stake should be remeasured during the 1989/90 season to determine the net mass balance over the interval. Some of the stakes will be broken or missing after winter storms, so they must be carefully identified, either by reading the small hand-written number or alternatively by determining their position (Fig. 22) relative to neighboring stakes. Anomalous results at a single stake are more likely to be due to the stake having settled or melted its way down through drill chippings than to any real local effect. The results of our measurements are shown in Table 2.

Table 2 Exposed height of stakes on 6 January 1989

Flag	Height (cm)	Flag	Height (cm)
1	148	18	146
3	155	19	154
4	127	20	150
5	152	6A	147
6	150	6B	155
7	152	6C	160
8	152	6D	152
9	145	6E	145
10	150	6F	154
11	147	6G	156
12	147	17A	143
13	150	17B	146
14	152	17C	158
15	144	17D	147
16	146	17E	136
17	147		

Trafficability

The best way to move about on the icefield is with conventional transport on wheels, not track-laying vehicles. Whether on wheels or tracks, LGP versions are not needed. There is more than one reason to avoid track-laying vehicles except where extreme draw-bar pull is required. Tracked vehicles can damage the brittle surface of the icefield and they leave more behind in the form of oil and grease. In contrast to South Pole, nothing left on the icefield will be concealed by snow; in a hundred years' time it will still be visible on the surface. Or worse, it can cause a glacier table (raised pedestal) or a cryoconite hole (possibly water-filled). Immense care must be taken to remove any kind of artifact or debris from the surface. In this connection, empty fuel drums should not be used as runway markers. To test the extent to which they do damage the surface, we carried three drums from the Beardmore Glacier (where they had lain since 1961) across the medial moraine to Mill Glacier. We left one each at Flags 1, 6, and 17. Runway markers should be held clear of the surface (as they are at South Pole) on uprights as small in their cross sectional area as practicable.

Construction

There are square kilometers of snow-free and stable permafrost terrain adjacent to the icefield on Meyer Desert. A city could be built there. The terrain is sufficiently level for conventional wheeled vehicles. Road-building would be straightforward and access to the icefield easy. Buildings can be erected on the icefield but over a period of years they would progressively appear to be raised up on a pedestal. Eventually they would fall off the pedestal.

CONCLUSION

Inland ice runways offer a ready means of operating conventional wheeled aircraft of any size at high latitudes. Preparation and maintenance costs are very low compared with any other kind of hard runway. The two sites that we have identified offer the advantage of overland access to South Pole. The dimensions and characteristics of the usable parts of these icefields would permit the operation of C-130, C-141, or C5B aircraft at maximum gross weight if necessary. Cargo and personnel could be flown in from the sea ice runway at McMurdo or alternatively direct from New Zealand or South America.

RECOMMENDATIONS

1. One or both of the sites that we have identified should be developed to operational status. The advantage of maintaining at least minimal facilities at both sites is that their long runways are at right angles to each other in grid terms, so that if one is experiencing turbulence or unacceptable crosswinds, the other can be used.

2. As soon as the concept is approved, LC-130 pilots should become familiar with the characteristics of inland ice runways in preparation for trial landings on wheels. The best way to do this is to fly the LC-130 pilots in with a Twin Otter so that they can walk over the icefield.

3. Automatic weather stations should be deployed at Howe and Mill icefields, Howe being the higher priority. In the absence of manned stations, this is the only way to ascertain normal weather patterns at the ice runway sites.

4. The aerial mapping photography completed in January 1989 should be used together with the leveling data to produce maps with 0.5 m contour interval. This should be done as soon as possible to provide the basis for final runway site selection.

5. Planing machinery should be taken into Howe icefield as soon as possible. The purpose would be to establish whether existing machinery is adequate, and if not, what modifications are necessary.

6. Twin Otter landings should be made on Reedy Glacier (around 85°45'S, 133°00'W), Mount Bumsted (85°39'S, 173°55'E), and Beardmore Glacier (around 85°20'S, 164°50'E) to see whether any of these sites might be worth investigating on the ground. While it is unlikely that any would have the merits of the sites selected, all possible alternates should be considered for use in an emergency.

7. The exposed length of all bamboo stakes left on Howe and Mill icefields should be remeasured during the 1988/89 season. This is necessary to determine the surface net balance, which has a direct bearing on the ease of maintenance of an ice runway. All these tasks (including those in para.3 above) can be accomplished by a Twin Otter in three flying days without camping gear.

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Appendix 1

HOWE RUNWAY 09 (207°true, 057°grid)

Distance (m)	Reduced level (m)	Flag	
0	0.0	1	(on steep ice slope)
82	+1.75	2	
168	2.99		
336	4.65		
484	5.88	3	
630	6.49		
856	7.10	4	
1080	7.15		
1408	8.40	5	
1707	10.21		
1807	11.69	6	
1892	12.49		
1997	13.52	7	
2191	14.09	8	
2473	12.41		
2589	12.82	9	
2747	12.73		
2895	15.48		
3036	18.25		
3046	18.43	10	
3258	20.97		
3334	21.40	11	
3420	21.69		
3520	22.23	12	
3625	22.57		
3839	22.77	13	
3960	22.15		
4075	21.60	14	
4286	20.47		
4576	19.03		
4927	17.98		
5107	17.35	16	
5236	16.91		
5450	15.77	17	
5720	14.46		
5922	14.00	18	
6044	13.56		
6321	11.54	19	
6407	9.92	20	
6528	7.49		
6657	5.69		
6747	4.51	21	
6816	1.29		
6888	2.71	(at edge of moraine)	

Appendix 2

HOWE CROSS LINE through flag 7 (180°magnetic, 297°true, 147°grid)

Distance (m)	Reduced level (m)	Flag
0	+6.95	
216	6.41	
316	9.21	
425	10.78	7A
606	12.69	
674	13.52	7B
830	14.32	
1085	16.37	
1170	17.50	7C
1326	18.04	7D
1748	18.35	7E
2049	17.24	
2341	16.17	
2642	13.83	(into small crevasses)

HOWE VALLEY LINE from flag 9 (180°magnetic, 297°true, 147°grid)

0	12.82	9
216	13.54	
282	14.30	9A
365	15.53	
504	16.93	9B
799	17.80	9C

HOWE CROSS LINE through flag 13 (180°magnetic, 297°true, 147°grid)

0	15.70	(backsight to edge of moraine)
289	17.31	
421	18.41	13A
520	19.53	
632	20.60	
712	21.71	
896	22.77	13C
1009	23.02	13D
1175	23.48	13E
1292	23.59	
1448	22.66	13F
1522	22.12	
1598	21.25	13G
1724	20.33	
1991	18.54	
2047	18.36	13H
2216	18.02	
2312	18.95	13I (at crevasses 30 cm wide)

Appendix 3

HOWE MICRORELIEF SURVEY

Reduced levels (m) 2.58 m apart along 090°magnetic from flag 11

(Read columns down and from left to right)

Level	Level	Level	Level	Level	Level	Level	Level	Level	Level	Level
0	+0.13	+0.15	+0.31	+0.41	+0.48	+0.54	+0.68	+0.72	+0.81	+0.85
+0.06	0.13	0.21	0.29	0.41	0.46	0.53	0.75	0.73	0.89	
0.08	0.16	0.24	0.33	0.51	0.45	0.56	0.66	0.74	0.77	
0.04	0.17	0.26	0.38	0.46	0.48	0.59	0.67	0.83	0.79	
0.08	0.13	0.26	0.37	0.41	0.56	0.64	0.72	0.75	0.77	
0.10	0.17	0.25	0.35	0.42	0.58	0.74	0.74	0.82	0.84	
0.08	0.18	0.29	0.37	0.45	0.53	0.62	0.71	0.81	0.85	

The same along 180°magnetic from flag 11

0	+0.04	+0.04	+0.26	+0.22	+0.52	+0.70	+0.76	+1.10	+1.44	+1.63
0	0.08	0.04	0.21	0.26	0.47	0.73	0.76	1.13	1.48	1.60
+0.01	0.12	0.05	0.17	0.29	0.48	0.75	0.78	1.14	1.48	1.61
0.01	0.19	0.05	0.13	0.29	0.50	0.74	0.82	1.17	1.40	1.51
0.05	0.20	0.09	0.08	0.28	0.50	0.73	0.80	1.16	1.43	1.52
0.06	0.10	0.15	0.11	0.30	0.53	0.78	0.83	1.15	1.46	1.55
0.06	0.10	0.21	0.12	0.35	0.55	0.80	0.87	1.15	1.43	1.57
0.08	0.10	0.10	0.11	0.38	0.57	0.83	0.91	1.15	1.43	
0.04	0.09	0.06	0.19	0.41	0.61	0.83	1.00	1.19	1.41	
0.02	0.10	0.07	0.20	0.44	0.67	0.80	1.05	1.19	1.44	
0.02	0.15	0.13	0.20	0.45	0.74	0.78	1.03	1.22	1.46	
0.05	0.09	0.21	0.19	0.48	0.80	0.83	1.01	1.28	1.44	
0.04	0.06	0.30	0.22	0.52	0.76	0.84	1.00	1.31	1.50	
0.04	0.08	0.24	0.21	0.55	0.70	0.80	1.03	1.28	1.50	
0.06	0.12	0.13	0.21	0.55	0.65	0.75	1.01	1.28	1.54	
0.04	0.07	0.14	0.21	0.51	0.67	0.73	1.01	1.28	1.61	
0.07	0.07	0.22	0.22	0.50	0.68	0.73	1.04	1.28	1.63	
0.07	0.06	0.24	0.23	0.51	0.64	0.73	1.10	1.38	1.66	

Appendix 4

MILL RUNWAY 36 (003°magnetic, 163°true, 329°grid)

Distance (m)	Reduced level (m)	Flag	Distance (m)	Reduced level (m)	Flag
0	+2.66		3654	48.43	
134	0	1	3780	50.40	12
321	+2.64		3821	50.89	
334	2.80	2	4040	52.89	
504	5.68		4165	54.06	13
633	8.50		4230	54.66	
684	9.52	3	4427	57.20	
823	11.44		4523	59.04	14
985	13.59		4585	60.13	
1011	13.95	4	4699	61.64	15
1176	16.32		4817	62.27	
1347	19.04		5038	64.83	
1363	19.30	5	5185	67.95	
1519	22.03		5286	70.61	
1614	23.56	6	5305	71.21	16
1677	24.60		5391	73.45	
1839	27.06		5526	76.43	
2010	29.39		5573	77.21	17
2056	30.04	7	5695	79.17	
2176	31.89		5831	81.33	
2341	34.71		5992	83.48	18
2416	35.86	8	6037	84.03	
2543	37.12		6233	86.67	
2678	38.45	9	6423	88.56	
2753	39.18		6467	89.17	19
2953	41.37		6595	90.88	
3095	43.55	10	6778	93.16	
3131	44.21		6964	95.59	
3305	46.45	11	7167	98.20	
3414	46.57		7295	99.93	20

Appendix 5

MILL CROSS LINE through flag 6 (268°magnetic, 068°true, 234°grid)

Distance (m)	Reduced level (m)	Flag	
0	11.64		(backsight to edge of moraine)
98	13.55		
232	15.46		
259	16.05	6A	
361	18.74		
456	21.26	6B	
621	22.88		
648	23.56	6	
918	24.66		
934	24.78	6C	
1127	25.06	6D	
1393	25.39		
1398	25.63	6E	
1423	24.40	6F	
1657	23.94		
1718	24.39	6G	
1974	25.24		
2213	24.89		
2563	23.45		
2794	23.30		(at giant rift)

MILL CROSS LINE through flag 17 (273°magnetic, 073°true, 239°grid)

0	63.90	17A	(on steep ice slope)
62	66.75		
149	70.14		
190	71.81	17B	
225	73.13		
299	75.80	17C	
377	77.21	17	
537	79.07	17D	
622	81.72		
650	83.99		
655	84.57		(at giant rift)